VOLUME L NUMBER 4

THE
JOURNAL OF GEOLOGY

May-June 1942

MODERN CONCEPTS OF THE PHYSICAL CONSTITUTION OF COAL[1]

GILBERT H. CADY[2]
Illinois State Geological Survey

ABSTRACT

The modern concepts of the physical constitution of coal involve megascopic recognition of four primary-type coals—vitrain, clarain, durain, and fusain—and subtypes due to variations of a microscopic order in the physical constitution of the primary-type coals. Most coal beds consist of composite associations of the primary-type coals. The technique of coal description has, in general, not kept pace with the technique of type differentiation. The validity of type classification has not been fully established by chemical evidence, which evidence, however, is strongly suggestive that the differences are real. The practical significance of type variations in coal lies in the fields of coal classification, coal preparation, and coal processing, including hydrogenation.

INTRODUCTION

The concept that coal may have a constitution possible of analysis in terms of its physical components is itself modern. Inquiry into the nature of the physical heterogeneity of coal began within the last twenty-five to thirty years, so that almost any concept in this field is a modern concept.

The study of the physical constitution of coal has attracted relatively few persons of geological training in this country, although rather more in other parts of the world. Lack of interest in the subject appears to be due to the fact that geological ideas in regard to

[1] Address delivered at the Fiftieth Anniversary Celebration, University of Chicago, September, 1941. Presented with the permission of M. M. Leighton, chief, Illinois State Geological Survey.

[2] Senior geologist and head of the Coal Division, Illinois State Geological Survey.

coal were established when its use was largely restricted to the high-rank coals. With respect to the variations in the physical constitution of these there was and is little point for concern. This same point of view has, unfortunately, been adopted by geologists in general toward the lower-rank coals, and expansion in the use of these coals has brought little immediate change in the geologist's attitude. Like the higher-rank coals, the coals of low rank were examined geologically and chemically and were used commercially in bulk without consideration of the existence or significance of physical heterogeneity.

However, the wide extension of the use of these coals, the mounting severity of competition, the common failure of the low-rank coals to perform with the same excellence as the higher-rank fuels, and the echoes of research announced abroad are circumstances stimulating curiosity concerning the nature and possible importance of the physical heterogeneity of the low-rank coals.

The present paper will be restricted to a discussion of the physical constitution of the mature coals,[3] namely, those of subbituminous, bituminous, and anthracite ranks. It is assumed that coals that have been subjected to equal amounts of geological vicissitude are of similar rank.

COAL VARIETIES

RANK VARIETIES

Two general categories of variation in coals are widely recognized. In one category are rank varieties,[4] effected by progressive metamorphism. More or less arbitrarily, although carefully, selected chemical criteria are used to differentiate coals of different rank. Physical criteria for differentiation also exist but are more difficult of absolute application.[5] It may be pointed out, however, that rough differentiation on physical grounds long preceded precise differentiation on chemical grounds.

[3] C. E. Marshall, "Contribution to the Comparative Petrology of British and American Coals of Carboniferous Age: Anthraxylon and Vitrinite (Vitrain)," *Fuel in Sci. and Pract.*, Vol. XX (1941), pp. 52–59, 82–91, particularly p. 53.

[4] Marshall, "Standard Specifications of Classification of Coals by Rank. A.S.T.M. Designation: D 388-38," *1939 Book of A.S.T.M. Standards Including Tentative Standards* (Philadelphia: Amer. Soc. Test. Materials, 1939), Part III, pp. 1–6.

[5] L. C. McCabe, "Some Physical Evidences of Development of Rank in Vitrain," *Fuel in Sci. and Pract.*, Vol. XVI, No. 9 (1937), pp. 267–86.

TYPE VARIETIES

More fundamental than variations caused by differences in rank are those caused by differences in the physical constitution or make-up of the coal. Variations in this category[6] produce what have been called "type varieties."

The importance of type variations of coal declines with advancing rank. Thus all anthracite of similar rank displays a great similarity of appearance, even though traces of an original heterogeneity of physical constitution may still be evident when the coal is specially prepared for inspection.[7]

In contrast with the physical homogeneity of the anthracites is the great heterogeneity in constitution of the mature coals of lower rank. It is with these coals that we are particularly concerned.

TYPES OF BITUMINOUS COALS ON THE BASIS OF MEGASCOPIC CRITERIA

BANDED AND NONBANDED COALS

Banded coals.—Inspection of a number of banded coals from various sources generally reveals the presence of four varieties of coal material, which have been called "banded ingredients" by Marie C. Stopes[8]—namely, vitrain, clarain, durain, and fusain (Fig. 1). The banded appearance or structure of all banded coals, whether bright or dull, is found to be due to the presence of layers, lenses, sheets, or fibers of jet-black vitrain or vitrain-like material of small dimensions. Bright-banded coals contain layers, lenses, or sheets of clarain with silky, bright luster between layers or bands of vitrain; dull-banded coals consist of interlayered vitrain and dull durain. A third variety of coal occurring in some beds of coal in benches, layers, or lenses is fusain or mineral charcoal.

Nonbanded coals.—What is commonly regarded as the banding of coals is due almost entirely to the presence of vitrain or vitrain-like

[6] McCabe, "Standard Definitions for Commercial Varieties of Bituminous and Subbituminous Coals, A.S.T.M. Designation: D 493-39," *1939 Book of A.S.T.M. Standards Including Tentative Standards*, Part III, p. 58.

[7] H. G. Turner and H. R. Randall, "A Preliminary Report on the Microscopy of Anthracite Coal," *Jour. Geol.*, Vol. XXXI (1923), pp. 306–13.

[8] "On the Four Visible Ingredients in Banded Bituminous Coals: Studies in the Composition of Coal, No. 1," *Proc. Roy. Soc. London*, Vol. XC (1919), p. 470; Stopes and R. V. Wheeler, *Monograph on the Constitution of Coal* (London: Dept. Sci. and Indust. Research, 1918).

PHYSICAL CONSTITUTION OF BITUMINOUS AND SUBBITUMINOUS COALS

CONSTITUENTS | COALS

MACERALS	PHYTERAL EQUIVALENTS	PRIMARY TYPE COALS ("BANDED INGREDIENTS")		COMPOSITE OR BANDED COALS	
THE INDIVIDUAL PHYSICAL COMPONENT OF COAL, USUALLY BUT NOT ALWAYS OCCURRING IN PHYTERAL FORM.	ANY FOSSIL PLANT FORM OR SECRETION RECOGNIZABLE AS AN ORGANIC ENTITY, EITHER ORGANIZED STRUCTURES (ROOTS, STEMS, PETIOLES, LEAVES, REPRODUCTIVE ORGANS, ETC) IN WHOLE OR IN PART, AND SECRETIONS HAVING CHARACTERISTIC FORM (WAXES, RESINS, ETC) GENERALLY WITH NO SPECIAL NAME	EACH COAL IS COMPOSED EITHER OF A SINGLE KIND OF MACERAL, WHICH MAY REPRESENT A SINGLE PHYTERAL OR CONSIST OF AN AGGREGATE OF MACERALS, COMMONLY BUT NOT ALWAYS OF MICROSCOPIC SIZE, AND COMMONLY BUT NOT ALWAYS OF DIVERSE KIND		THESE COALS CONSIST OF INTERLAMINATED AGGREGATES OF PRIMARY-TYPE COALS ("BANDED INGREDIENTS"). THE BANDED STRUCTURE IS DUE MAINLY TO THE PRESENCE OF VITRAIN OR MICROVITRAIN. THERE ARE TWO MAJOR CLASSES: BRIGHT AND DULL	
		TYPES	VARIETIES	GENERAL VARIETIES	SPECIAL VARIETIES
MORE COMMON MACERALS:	IN BOTH LARGE & SMALL UNITS:	(MAINLY AS INGREDIENTS, BUT MAY COMPOSE THE ENTIRE BENCH OR BED)		BRIGHT BANDED COALS: CONSIST OF-	
Vitrinite (Occurs as Vitrain in bands more than .10-in. thick (2 mm.); as microvitrain in bands 2 mm. to 0.05 mm. thick; and as humic degradation matter less than 0.05 mm. Varities depend on composition but none specifically recognized. Usually contains cell traces.)	Roots, stems, leaves, petioles, etc. (Muralite of various kinds)	**Vitrain (Anthraxylon)** CONTAINS: VITRINITE ± Resinite (At least 2 mm. (0.1-in) thick)	Depending on the kind of plant represented and on presence or absence of resinite.	**Vitrain and** CLARAIN ± minor Durain and minor Fusain, OR **Clarain with** MICROVITRAIN ± minor Durain and minor Fusain.	Determined by the amount of vitrain and its character and thickness, (More than 0.5 in thick banded, 0.5 to 0.1 in. thin banded) and character of clarain. VARIETIES UNNAMED Vitrain may rarely be banded with cannel to form a bright banded cannel.
Fusinite (Occurs as Fusain or as particles or small aggregates in Clarain and	Roots, stems, leaves, petioles, etc. (Muralite of various kinds)	**Fusain** CONTAINS:	Unrecognized		
Resinite (Occurs in Vitrain, Clarain, Durain, and Fusain)	Resin cavities and droplets occurring in in cavities of stems, in Vitrain, and Fusain, or in discrete particles in Clarain, Durain, and Fusain.	**Clarain** CONTAINS: Vitrinite as microvitrain and humic deg-			

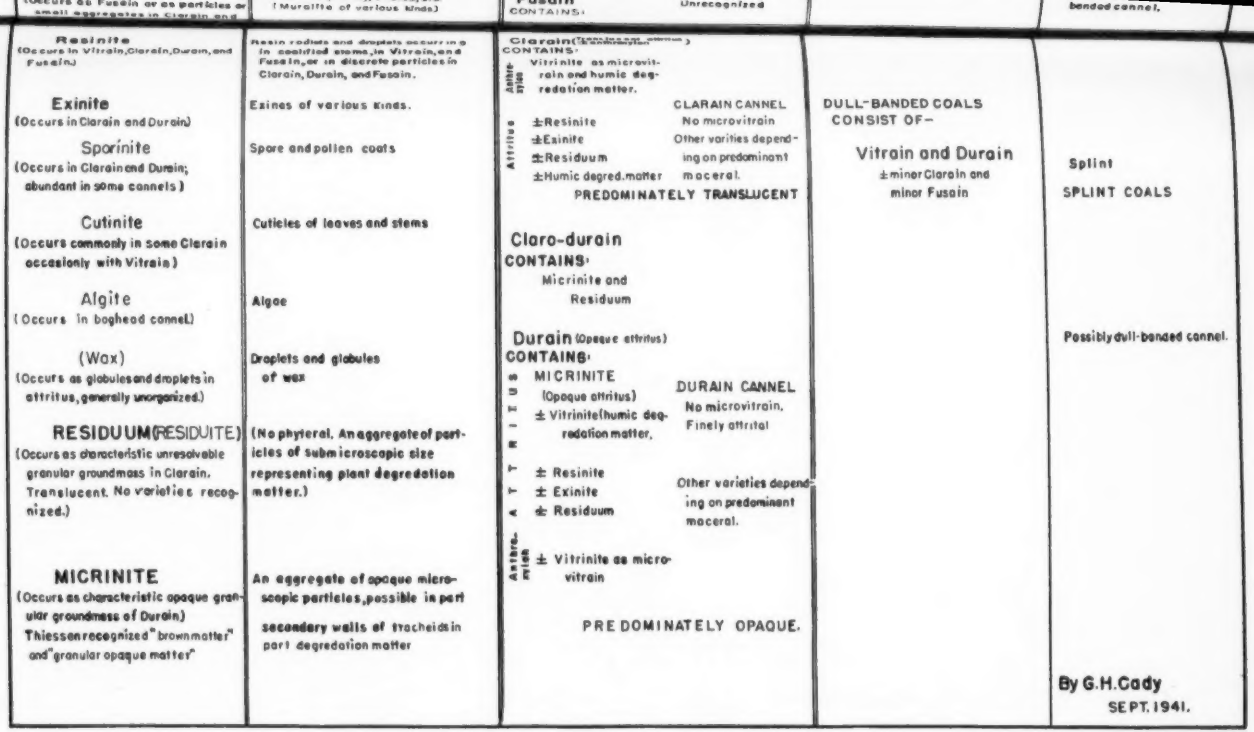

Resinite
(Occurs in Vitrain, Clarain, Durain, and Fusain.)
Resin rodlets and droplets occurs in g in cavities and cells, in Vitrain, and Fusain, or in discrete particles in Clarain, Durain, and Fusain.
Exinite
(Occurs in Clarain and Durain)
Exines of various kinds.
Sporinite
(Occurs in Clarain and Durain; abundant in some cannels)
Spore and pollen coats
Cutinite
(Occurs commonly in some Clarain occasionly with Vitrain)
Cuticles of leaves and stems
Algite
(Occurs in boghead cannel)
Algae
(Wax)
(Occurs as globules and droplets in attritus, generally unorganized.)
Droplets and globules of wax
RESIDUUM (RESIDUITE)
(Occurs as characteristic unresolvable granular groundmass in Clarain. Translucent. No varieties recognized.)
(No phyteral. An aggregate of particles of submicroscopic size representing plant degredation matter.)
MICRINITE
(Occurs as characteristic opaque granular groundmass of Durain)
Thiessen recognized "brown matter" and "granular opaque matter"
An aggregate of opaque microscopic particles, possible in part secondary walls of tracheids in part degredation matter
Clarain
CONTAINS:
Anthrinite
Vitrinite as microvitrain and humic degredation matter.
Attritus
±Resinite
±Exinite
±Residuum
±Humic degred. matter
CLARAIN CANNEL
No microvitrain
Other varities depending on predominant maceral.
PREDOMINATELY TRANSLUCENT
Claro-durain
CONTAINS:
Micrinite and Residuum
Durain (Opaque attritus)
CONTAINS:
ATTRITUS
MICRINITE
(Opaque attritus)
± Vitrinite (humic degredation matter,
DURAIN CANNEL
No microvitrain, Finely attrital
± Resinite
± Exinite
± Residuum
Other varieties depending on predominant maceral.
Anthrinite
± Vitrinite as microvitrain
PREDOMINATELY OPAQUE.
DULL-BANDED COALS CONSIST OF-
Vitrain and Durain
±minor Clarain and minor Fusain
Splint
SPLINT COALS
Possibly dull-banded cannel.
By G.H.Cady
SEPT. 1941.

FIG. 1

material of small dimensions. Nonbanded coals, on the other hand, contain essentially no vitrain. Cannels are typical examples of such coals, but probably not all nonbanded coals are generally regarded as cannels. Nonbanded coals consist of clarain or durain or of material intermediate between the two.

PRIMARY-TYPE COAL

The varieties of coal which compose the banded and unbanded coal beds, to which the term "banded ingredients" was applied by Stopes in 1919[9] and "rock types" in 1935[10] are regarded by the writer as primary types of coal. This belief is in accordance with what appears to be Stopes's conception of the ingredients as the four fundamental varieties of bituminous coal into which all such coal can be resolved. Whether they are called "primary types," "rock types," or "ingredients" is of minor importance, provided the same implication of terms is maintained. The terms will be used interchangeably in the present paper.

The primary-type coals or ingredients were originally differentiated on the basis of megascopic criteria,[11] which have since been supported to a greater or less degree by microscopic criteria.[12] There has been considerable confusion in understanding and terminology mainly because of what must be regarded as ill-advised[13] initial declarations concerning the microscopic identifications, later largely cleared up,[14] but partly because of the parallel development of a genetic system of terminology in the United States and partly because of a lack of standardization of microscopic technique employed in different parts of the world. This confusion is gradually disappearing; but, unless there is considerable expansion of the meager literature dealing with the subject of the physical constitution of coal, complete clarification cannot be expected for a number of years.

The banded ingredients have been described many times and

[9] "On the Four . . . . ," *op. cit.*

[10] Stopes, "On the Petrology of Banded Bituminous Coals," *Fuel in Sci. and Pract.*, Vol. XIV, No. 1 (1935), pp. 4–13.

[11] Stopes, "On the Four . . . . ," *op. cit.;* Stopes and Wheeler, *op. cit.*

[12] Stopes, "On the Petrology . . . . ," *op. cit.*

[13] Stopes, "On the Four . . . . ," *op. cit.;* Stopes and Wheeler, *op. cit.*

[14] Stopes, "On the Petrology . . . . ," *op. cit.*

fairly recently by the writer.[15] It is unnecessary to repeat definitions and descriptions with which there is familiarity. Consideration will be given, therefore, only to some of the more or less controversial matters involving the identification of these primary-type coal materials.

Vitrain.—As far as the writer is able to discover, there is no disagreement, on the basis of *megascopic* characteristics, in regard to the kind of coal material that Stopes named "vitrain." Controversy has developed mainly as a result of disagreement concerning the validity of the initial *microscopic* characterization of vitrain,[16] some workers having accepted this characterization as valid,[17] others not being willing to do so.[18] Hence, one group of technologists claims that vitrain is composed of structureless material and another that there is no structureless vitrain.

Uncertainty has developed concerning the application of the term "vitrain" to vitrain-like material of small dimensions which may make up a considerable portion of a clarain layer or band. The same material, it is felt, should not be called both "vitrain" and "clarain."

The distinction is obviously mainly one of size. Arbitrary limits will eventually be necessary and some terminology proposed. The writer, since he has already used the term,[19] suggests that the thin vitrain-like bands composing clarain shall be called "microvitrain," meaning small vitrain rather than vitrain necessarily of microscopic width. There is practical justification in setting a limitation between vitrain and microvitrain as it occurs in coal at about $\frac{1}{10}$ inch (2 mm.) with a tolerance of 1 millimeter, for it has been shown[20] that in the natural breakage of coal the thicker vitrain bands tend to break away from the rest of the coal and to concentrate in the small-screen sizes.

[15] "Nomenclature of the Megascopic Description of Illinois Coals," *Econ. Geol.*, Vol. XXXIV, No. 5 (1939), p. 487.

[16] Stopes, "On the Four . . . . ," *op. cit.*

[17] André Duparque, "Structure microscopique des charbons du bassin houiller du nord et du Pas de Calais," *Mem. Soc. géol. du nord*, Vol. XI, Part I (1923), pp. 150–72.

[18] Reinhardt Thiessen, "What Is Coal?" (Cincinnnati: Appalachian Coals, Inc., 1937), pp. 22–26. (Planographed.)

[19] *Op. cit.*

[20] McCabe, "Changes in the Constitution of Illinois Coal through Preparation Processes," *Mining Cong. Jour.*, Vol. XXIII (1937), pp. 18–19.

The minimum width of microvitrain as distinct from attrital humic matter is set at 0.05 millimeter (50 μ) in accordance with the practice followed by Thiessen.[21]

A second reason for differentiating vitrain and microvitrain is in line with certain suggestions made by Thiessen. Although he established no categories of size-differentiation of anthraxylon (the equivalent of vitrain) down to at least 0.05 millimeter (50 μ), nevertheless, he did call attention to a distinction between thick and thin bands. Thus he said:

> While the thicker bands are almost exclusively derived from the wood, periderm, or bark of the stems, the smaller ones may be derived from leaf basis, petioles, rachis, sporophylls and sporangia, as well as from the woody part and barks of the stems.[22]

The tentative selection of about $\frac{1}{10}$ inch as an arbitrary megascopic dimensional boundary between bands of vitrain and microvitrain in the bed, bench, or hand specimen of coal, to satisfy the necessity for quantitative determinations, will probably exclude from vitrain all vitrain-like material not derived from stems and in general will not include in the vitrain the microvitrain characteristic of the smaller broken sizes of coal between the dimensions of about 2 inches and about $\frac{1}{4}$ inch. After coal is crushed to a powder the vitrain-like material present cannot be differentiated as having originated either as vitrain or as microvitrain.

Fusain.—No particular difficulty exists with respect to the identification or the nomenclature of fusain. Fusain may be hard or soft, depending upon whether or not it has been mineralized. Semifusain[23] is material transitional between vitrain and fusain, like a half-charred piece of wood.

Estimation of the quantity of fusain present in a coal is of practical interest in planning for dedusting and dust-settling operations designed to benefit the coal.[24] This can be done by screen analysis

[21] A. C. Fieldner *et al.*, "Methods and Apparatus Used in Determining the Gas, Coke, and By-product Making Properties of American Coals," *U.S. Bur. Mines Bull. 344* (1931), p. 69.

[22] "What Is Coal?" p. 26.

[23] Otto Stutzer and Adolph C. Noé, *Geology of Coal* (Chicago: University of Chicago Press, 1940), p. 71.

[24] Thiessen, "Fusain Content of Coal Dust from an Illinois Dedusting Plant," *Amer. Inst. Min. and Met. Engineers Tech. Pub. No. 664* (1936).

and fusain counts,[25] but the Fuchs method of selective oxidation[26] has been found more practical.[27]

Clarain.—Clarain has proved the most troublesome to identify and describe of the primary-type coals or ingredients. This is mainly because it may be composed very largely of microvitrain. It may be entirely omitted from the picture, as is done by Thiessen[28] and by Erich Stach;[29] or the concept may be redefined and enlarged to include vitrain as well as microvitrain, as was done recently by A. Raistrick and C. E. Marshall.[30] Acceptance of a $\frac{1}{10}$-inch limitation as the minimum width of vitrain may help to allay this uncertainty in identification and description, unless fundamental considerations are at stake not evident to the present writer.

Durain.—It is generally agreed that durain is dull attrital coal, characterized by a high proportion of opaque material.[31] The characteristics of durain, generally called "splint coal" in America, have been described at length by Thiessen, by Thiessen and Sprunk, and by Sprunk and others.[32]

The differentiation of clarain and durain has also given difficulty. When either coal possesses its characteristic appearance, the clarain being bright and the durain dull, there is no great difficulty in their identification. It is the intermediate coals that give difficulty, particularly the rather dull clarain coals. It seems appropriate to designate these by the term "duro-clarain." Attrital coal of this inter-

[25] Bryan C. Parks and L. C. McCabe, "Fusain Content of Fine Sizes of Illinois Coals," *Trans. Ill. State Acad. Sci.*, Vol. XXXIII (1940), pp. 164–68.

[26] W. Fuchs *et al.*, "The Chemistry of the Petrographic Constituents of Bituminous Coal: I. Studies on Fusain," *Penn. State Coll., Min. Indust. Exper. Stat. Bull. 23* (1938).

[27] B. C. Parks *et al.*, "A Comparison of Chemical and Petrographic Methods of Determining the Fusain Content of Illinois Coal" (paper read before the Gas and Fuel Division, American Chemical Society, Atlantic City, September, 1941).

[28] "What Is Coal?" pp. 30–33.

[29] *Lehrbuch der Kohlenpetrographie* (Berlin: Gebrüder Borntraeger, 1935), pp. 23–95.

[30] *The Nature and Origin of Coal and Coal Seams* (London: English Universities Press, Ltd., 1939), p. 180.

[31] *Ibid.*

[32] Thiessen, "What Is Coal?"; Fieldner *et al.*, *op. cit.*; R. Thiessen and George C. Sprunk, "The Origin of the Finely Divided or Granular Opaque Matter in Splint Coals," *Fuel in Sci. and Pract.*, Vol. XV (1936), pp. 304–15; Sprunk *et al.*, "Splint Coals of the Appalachian Region—Their Occurrence, Petrography and Comparison of Chemical and Physical Properties with Associated Bright Coals," *U.S. Bur. Mines Tech. Paper 615* (1940).

mediate character, it is believed, composes the attrital portion of the coals called "semisplint" by Thiessen.[33]

There is a distinction of possible importance between splint coal and durain. Splint coal was apparently regarded by Thiessen[34] as one of the varieties of banded coals containing both anthraxylon (vitrain) and attritus. It is the name of a mixed or composite coal and not the name simply of the dull, attrital part of such coal, which is durain.

In England durain is commonly known by the name "hard coal" or "hards,"[35] occurring as benches in coal beds otherwise consisting of bright-banded coals, vitrain, and clarain. In Germany this kind of coal is called *Mattkohle*.

CANNELS

Cannels are attrital, finely microclastic, nonbanded coals. They may belong either to the clarain or to the durain primary types of coal. This classification depends in a general way upon whether they appear bright or dull, but final decision depends upon whether thin sections of the coal are translucent or opaque. The name carries certain connotations concerning fineness of grain, density, fracture, luster, and temperature of ignition that are generally applicable. A considerable variety of such coals exist, which can be conveniently classified as either clarain cannels or durain cannels.[36] The subordinate character of the components of cannel is subject to considerable variation and determines the subvariety of such cannel. Thiessen lists six such varieties.[37]

THE COMPOSITE COALS

In their most common mode of occurrence the primary-type coals or ingredients are associated as contiguous layers to comprise composite varieties of coal in beds or benches. Conversely, the composite coals are megascopically resolvable into two or more of the primary-type coals or ingredients.

Each ingredient may compose an entire bed or bench of coal, but such a bed or bench of coal is not a composite coal.

[33] "What Is Coal?" p. 35.

[34] *Ibid.*, pp. 30–33.

[35] Raistrick and Marshall, *op. cit.*, p. 200.

[36] Thiessen, "Recently Discovered Methods of Research in the Constitution of Coal and Their Application to Illinois Coals," *Ill. State Geol. Surv. Bull. 60* (1931), p. 124.

[37] *Ibid.*, p. 125.

THE MICROSCOPIC CONSTITUENTS: MACERALS AND PHYTERALS

Primary-type coals are not themselves of uniformly similar composition, because of variations in their physical constitution, the nature of which it is possible to determine only by microscopic examination of the coal. This statement introduces consideration of the macerals and "phyterals."

Macerals have been called by Stopes[38] the "petrologic units" of the rock types, corresponding to minerals in sedimentary and igneous rocks. The writer has believed for some time that there is need for another term to designate plant forms or fossils in coal as distinguished from the material of which the fossils may be composed, as long as this is organic matter. To meet this need the term "phyteral" (Φυτον, Gr. meaning "plant" and *-eral* in "mineral") is proposed. In general, macerals seem to be less persistent as individual substances than are phyterals as fossil forms, since phyterals may be discovered in high-rank coals in which macerals no longer appear to exist as distinct substances. The term "phyteral" should be used as essentially equivalent to the phrase "coal fossil" or "coalified fossil" or as "fossil" is used in descriptions of sedimentary rocks.

The composition of the primary coal types is determined by the nature of the macerals of which each is composed.

THE PHYTERALS AND MACERALS OF THE PRIMARY COAL TYPES

Vitrain is composed to a greater or less extent of the maceral vitrinite.[39] According to Stopes, vitrinite has a number of meanings, but the material is primarily a "translucent golden gel." In some vitrain certain phyterals are present which consist of traces of cellular structure representing cell walls of various parts of the stems or roots of plants. This cellular structure—the form not the substance—it is proposed to designate by the term "muralite" (*muralis*, "of walls").

The plants and plant parts and forms represented by muralite in vitrain have been described at length by H. G. A. Hickling and C. E. Marshall,[40] by Raistrick and Marshall,[41] and by Thiessen.[42]

[38] "On the Petrology . . . . ," *op. cit.*, pp. 6–7. [39] *Ibid.*

[40] "The Microstructure of the Coal in Certain Fossil Trees," *Trans. Inst. Min. Engineers*, Vol. LXXXIV, Part II (1932), pp. 13–23; Vol. LXXXVI, Part II (1933), pp. 56–75.

[41] *Op. cit.*, pp. 181–90. [42] "What Is Coal?" pp. 22–26.

It is uncertain whether or not the substances represented by these cellular forms of muralite actually exist as macerals distinct from the vitrinite. If they do, the character of the vitrain presumably varies with variation in the character of the maceral.

Some vitrain contains in addition to vitrinite more or less resinite,[43] which is the substance of resin rodlets or other forms of resinous secretory matter which occupied cell cavities in the tissues which have been vitrinized. Occasionally resinite will make up a considerable portion of a vitrain band. Resinite has somewhat different properties than vitrinite, as has been shown by studies made by Thiessen and Sprunk[44] on the effect of heat on coals as revealed by the microscope.

The attrital coals—durain and clarain—are commonly composed of a variety of plant materials (macerals) of various derivations. Thiessen has listed the components of attrital coals as "humic degradation matter, small fragments of plant tissue, cuticles, spore and pollen exines, resin particles, and mineral matter."[45] Such coals also may contain fragments of fusain.

The distinctive feature of the components of clarain is their translucency in thin sections. Durain, on the other hand, is prevailingly opaque.

Composing clarain, besides the macerals which represent recognizable phyterals or plant forms, there is usually a groundmass of translucent material, the units of which are of submicroscopic size, which constitutes the "residuum" (residuite?) of Stopes.[46] Clarain may also contain some opaque matter, the "micrinite" of Stopes.

The components of durain—the essential ingredient of splint coals—are much the same as those of clarain except that there is a large proportion of submicroscopic material consisting predominantly of opaque micrinite.

THE SIGNIFICANCE OF MACERALS IN THE DESCRIPTION AND CLASSIFICATION OF COALS

The megascopic classification of bituminous coal is determined by the ingredients or primary-type coals that are present. More precise

[43] Stopes, "On the Four . . . . ," *op. cit.*

[44] "The Effect of Heat on Coal as Revealed by the Microscope," *Fuel in Sci. and Pract.*, Vol. XIII (1934), pp. 116–25.

[45] Fieldner *et al.*, *op. cit.*, p. 23. [46] "On the Petrology . . . . ," *op. cit.*, pp. 6–7.

classification is dependent upon microscopic determination of the identity and relative abundance of the macerals of which the ingredients may be composed.

The individuality of the macerals is indicated in a number of ways: by the fact that they are the substance of forms (phyterals) having organic individuality; by their physically individual and peculiar properties; and by the fact that coals of the same rank but of different physical composition differ in properties and behavior.

Subvarieties of the ingredient or primary-type coals result from characteristic concentrations of individual macerals, giving the coal special and specific properties.

TECHNIQUE OF COAL STUDY

MICROSCOPIC TECHNIQUE

Microscopic technique in the study of coal has not changed materially for many years,[47] but the quality of the tools has greatly improved, and the purpose of such studies has changed. Three methods have long been employed for the preparation of coal for examination by the microscope: the polished surface,[48] thin sections,[49] and macerated residues.[50] In England and America thin sections are preferred, if they can be made, because their use makes possible more certain identification of the macerals and phyterals. On the Continent less use is made of thin sections, with some important exceptions.

[47] Stach, *op. cit.*, p. 129; Thiessen and Sprunk, "Microscopic and Petrographic Studies of Certain American Coals," *U.S. Bur. Mines Tech. Paper No. 564* (1934), p. 10; Thiessen, "Microscopic Study of Coal" in David White and Reinhardt Thiessen, "The Origin of Coal," *U.S. Bur. Mines Bull. 38* (1913), pp. 187–304; Thiessen *et al.*, "Preparation of Thin Sections of Coal," *U.S. Bur. Mines Inf. Circ. No. 7021* (1938); W. Hutton, "Observations in Coal," *Phil. Mag.*, Vol. II (1833), pp. 302–4; also *Proc. Geol. Soc. London*, Vol. I (1884), pp. 415–47.

[48] Duparque, *op. cit.;* H. Winter, "The Examination of Coal by Reflected Light," *Fuel in Sci. and Pract.*, Vol. II (1923), pp. 78–82. (Previously published in German, *Glückauf*, Vol. XL [1913], pp. 1406–13.)

[49] Hutton, *op. cit.;* Thiessen *et al.*, *op. cit.;* Winter, *op. cit.*

[50] Franz Schultze, "Über des Verkommenwohlerhaltenes Cellulose im Braunkohle und Steinkohle," *Ber. kgl. Akad. d. Wissensch. Berlin* (1885), pp. 676–78; C. W. von Gümble, "Beiträge zur Kenntnis der Textureverhältnisse der Mineralkohlen," *Sitzungsber. kgl. bayr. Acad. Wissensch.* (München), Vol. XIII (1883), pp. 111–216; Hutton, *op. cit.*

TECHNIQUE OF DESCRIPTION AND CLASSIFICATION

Megascopic description.—Megascopic description of the composite or banded coals in accordance with specifications based upon the data of physical constitution has not been standardized. Suitable nomenclature, were it set up, would serve as a short cut to the description of special varieties of coal. At present the only special variety of banded coal to which a name with technical significance has been applied is splint coal. The generalized names "bright banded" and "dull banded" are useful but give little idea concerning the specific characteristics of a particular bright- or dull-banded coal.

The purpose of description is twofold: First, it should provide information in regard to the coal which has significance in terms of utilization or adaptability for utilization and, second, its purpose is technical and scientific, to provide a basis for comparison and classification.

In order to meet the requirements of megascopic description it is believed that any schedule of descriptive procedure applied to a banded or composite variety of coal should include provision for supplying the following information: (1) whether the coal is bright or dull banded; (2) the relative amount of each of the ingredients or primary types of coal; (3) the prevailing width of the vitrain bands —in many cases the number of such bands can be stated; (4) the amount of microvitrain in the clarain and durain; (5) the character of the attrital portion of the clarain and the durain (silky, dull black, grayish-black); (6) the amount and mode of occurrence of the fusain in layers, sheets, lenses, or particles; and (7) the character and distribution of the mineral matter in the bands and layers of the ingredient coals.

Only as systematic description and type specimens become available will an orderly grouping of the composite or banded bituminous coals be achieved.

FIELD DESCRIPTION OF COALS

The conventional practice with respect to field description of coal beds has shown little change in recent years, in contrast to the improvement in laboratory description. Coal beds are rarely described in the field in terms of their physical constituents, so that in general

the descriptions fall far short of providing information suitable for megascopic classification or for indicating the probable behavior of the coal in preparation and utilization.

DESCRIPTION BASED UPON MICROSCOPIC EXAMINATION

Description of column samples.—The graphic method of describing the coal in columns cut from the bed has had fairly wide use.[51] Coal-bed profiles based upon microscopic examination of the coal appear in the works of F. L. Kühlwein, E. Hoffman, and E. Krüpe,[52] G. Roos,[53] Adam Drath and Stanislaw Jaskowski,[54] and R. G. Koopmans.[55]

The United States Bureau of Mines for about ten years has employed a graphic profile system of describing column sections of coal beds.[56] The profile is plotted on the basis of microscopic examination of units of about 20 millimeters of the column. Types of coal are delineated as bright, semisplint, or splint. Subtypes are set up on the basis of the amount of anthraxylon and attritus present, irrespective of the size of the anthraxylon (vitrain and microvitrain) bands. The width of banding is plotted as coarse, fine, or microbanded. Text descriptions accord with data shown in the graphic section.

The profile method has also been very commonly used in plotting megascopic variations in measured sections of coal beds. Numerous profiles of British coal beds appear in the reports of the Physical and Chemical Survey of the National Coal Resources.[57] Graphic profiles

[51] F. L. Kühlwein, "Bedeutung der angewandten Kohlenpetrographie für Kohlengewinnung, Kohlenaufbereitung, und Kohlenveredelung," *Compt. rend. deuxième Cong. p. l'avance d. études strat. carbonifère, Heerlen, 1935*, Vol. II (1937), pp. 539–601.

[52] "Durchführung und praktische Bedeutung planmässig Kohlenpetrographische Flozprofiluntersuchungen," *Glückauf*, Vol. LXX (1934), pp. 1–28, 32–41.

[53] "Comparative Researches on the Variation of the Constituents of Coal of One Seam from South Limburg (the Netherlands)," *Compt. rend. deuxième Cong. p. l'avance d. études strat. carbonifère, Heerlen, 1935*, Vol. II (1937), pp. 1106–27.

[54] "Petrographical Investigations of the Otto Coal Bed, Radzionkow Mine, Upper Silesia," *Ann. Polish Geol. Soc.* (Krakow), Vol. XII (1936), pp. 685–77 (Polish, with Eng. summary).

[55] "Petrographische Profile niederlandischer Flöze," *Compt. rend. deuxième Cong. p. l'avance d. études strat. carbonifère, Heerlen, 1935*, Vol. II (1937), pp. 523–26.

[56] Fieldner *et al.*, *op. cit.*, p. 66.

[57] Koopmans, "The Northumberland and Durham Coalfield," *Dept. Sci. and Indust. Research, Phys. and Chem. Surv. Nat. Coal. Resources No. 41* (1937), p. 9; and numerous other reports of similar character by this department.

are the standard method used by the United States Geological Survey[58] for delineating thickness of beds and the distribution and thickness of interbedded impurities, but the physical constitution of the coal itself is not shown graphically in publications of that survey.

DESCRIPTION OF PREPARED COALS

The technique of measuring the quantity of the various primary-type coals in masses of broken coal is unsatisfactory. Screening and counting of particles of similar size will achieve the desired results but are very laborious.[59] The Fuchs's chemical method of fusain determination has been mentioned.[60] The accurate measurement of the quantity of vitrain, clarain, and durain, as well as fusain, in small sizes of broken coal is a matter of critical importance, if the relative quantity of these primary-type coals is significant in utilization, as has been claimed by James Lomax,[61] O. de Booseré,[62] M. Legraye,[63] and McCabe and associates.[64] This problem is under investigation at the present time in Urbana.

PALEOBOTANY AND THE PHYSICAL CONSTITUTION OF COAL

The physical constitution of coal has a closely knit relationship to paleobotany. Three lines of investigation have proved mutually fruitful within recent years. These are, first, the study of residues, particularly spore coats, obtained by the maceration of coal;[65] sec-

[58] Frank S. Parker and David A. Andrews, "The Mizpah Coal Field, Custer County, Montana," *U.S. Coal Surv. Bull. 906-C* (1939), Pls. XXVIII–XL; and numerous other reports on coal fields by other authors.

[59] Parks and McCabe, *op. cit.* [60] Fuchs *et al.*, *op. cit.*

[61] "Further Researches in the Microscopical Examination of Coal, Especially in Relation to Spontaneous Combustion," *Trans. Inst. Min. Engineers*, Vol. XLVI (1913–14), pp. 592–635.

[62] "Sur les constituants macroscopiques des charbons campanois," *Ann. d. mines de Belge*, Vol. V (1926), pp. 522–27; in English in *Fuel in Sci. and Pract.*, Vol. V (1926), 522–27.

[63] *Les Constituants des charbons, leur influence sur quelques propriétés industrielles* (Paris: Dunod, 1933).

[64] McCabe, "Illinois Coals. Constitution. Importance with Reference to their Utilization," *Mech. Engineering* (March, 1938), pp. 217–21; McCabe *et al.*, "Banded Ingredients of No. 6 Coal and Their Heating Value as Related to Washability Characteristics," *Ill. State Geol. Surv. Rept. of Inv. No. 34* (1934), p. 42.

[65] James M. Schopf, "Spores from the Herrin (No. 6) Coal Bed in Illinois," *Ill. State Geol. Surv. Rept. Inv. No. 50* (1938).

ond, the study of coal-ball petrifactions, large collections of which have become accessible to paleobotanists during the past decade, largely owing to their initial identification by the late Professor A. C. Noé;[66] and, third, the study of vitrain bands, representing the coalified solid portion of stems of various plants.[67]

CHEMICAL INDIVIDUALITY OF THE PHYSICAL COMPONENTS OF COAL

For evidence of the chemical individuality of the physical components of coal essentially the only sources, for American coals at

TABLE 1*

ANALYSES OF A FACE SAMPLE AND SAMPLES OF HAND-PICKED VITRAIN, CLARAIN, DURAIN, AND FUSAIN FROM HERRIN (NO. 6) BED COAL NEAR WEST FRANKFORT, FRANKLIN COUNTY, ILLINOIS

Kind	Lab. No.	Moisture	Vol. Mat.	Fixed Carb.	Ash	H	C	N	O	S	B.t.u.	Unit B.t.u.
Face	B-26213	8.9	35.3†	48.8	7.0	5.6	68.6	1.5	15.9	1.4	12,170	
			38.8‡	53.5	7.7	5.0	75.3	1.6	8.9	1.5	13,360	
			42.0§	58.0	.....	5.4	81.5	1.7	9.7	1.7	14,470	14,622
Vitrain	C-1999	9.0	31.6	58.5	0.9	5.57	74.65	1.71	16.45	0.72	13,009	
			34.7	64.3	1.0	5.02	82.03	1.88	9.28	0.79	14,296	
			35.1	64.9	.....	5.07	82.85	1.90	9.38	0.80	14,438	14,476
Clarain	C-1995	8.3	31.1	46.1	14.5	5.08	62.90	1.60	13.97	2.00	11,272	
			33.9	50.3	15.8	4.53	68.59	1.74	7.20	2.18	12,292	
			40.3	59.7	.....	5.39	81.47	2.07	8.46	2.59	14,600	14,888
Durain	C-1996	3.7	49.9	42.8	3.6	6.29	77.06	1.56	10.03	1.45	14,249	
			51.8	44.5	3.7	6.11	80.01	1.62	7.00	1.51	14,795	
			53.8	46.2	.....	6.34	83.13	1.68	7.29	1.56	15,371	15,467
Fusain	C-1997	8.1	8.4	79.8	3.7	3.11	85.56	0.63	6.41	0.64	13,800	
			9.1	86.9	4.0	2.73	89.70	0.66	2.41	0.67	15,011	
			9.5	90.5	.....	2.83	92.27	0.69	2.51	0.70	15,632	15,716

* Face sample analyzed by U.S. Bureau of Mines; others by Analytical Division, Illinois State Geological Survey.

† As received. ‡ Moisture free. § Moisture and ash free.

least, are the data supplied in the conventional proximate and ultimate forms of analysis. There are gradually being assembled in the laboratories of the United States Bureau of Mines and the Illinois State Geological Survey, and possibly in others, analytical data relative to the primary-type or ingredient coals. The ingredients can be

[66] "Review of American Coal-Ball Studies," *Trans. Ill. Acad. Sci.*, Vol. XXIV (1931), pp. 317–20.

[67] Marshall, "Contribution to . . . . ," *op. cit.*; Thiessen, "What Is Coal?" Raistrick and Marshall, *op. cit.*; Hickling and Marshall, *op. cit.*

separated relatively easily by hand in quantities sufficiently large for purposes of analysis. The resulting analyses often show interesting relationships, but the amount of data does not justify more than suggestive generalizations (Table 1).

Inspection of Table 1 reveals that clarain and the face sample, except for the high ash content of the clarain, are essentially alike. In contrast, the ash content of the vitrain is very low; the fixed and total carbon values are higher, and the hydrogen value somewhat lower, than in clarain and in the whole coal. Durain is characterized by a reversal of the fixed-carbon and volatile-matter relationship as compared with the other coals. Another sample of durain from the same mine gave essentially duplicate values. Fusain has the highest fixed-carbon and total-carbon values—each above 90 per cent—and a very low hydrogen content. These analyses indicate the nature of the evidence concerning the chemical characteristics of the ingredient coals that may be supplied by the commercial types of analysis.

Such data as these provoke the curiosity of the coal geologist concerning the real chemical structures represented by the coal macerals and the ingredient coals. It will be impossible to define these materials chemically until a large volume of proximate and ultimate analytical data is assembled or until the true chemical structure is systematically investigated.

PRACTICAL SIGNIFICANCE OF THE PHYSICAL CONSTITUTION OF COAL

COAL CLASSIFICATION AND DESCRIPTION

Certain phases of the classification of coal into types are perhaps mainly of academic interest, but it is believed that development and general acceptance of such a classification will result in improved technique in laboratory and particularly in field description. Such acceptance probably must precede the general adoption of discriminating methods of selection in the preparation and processing of subbituminous and low-rank bituminous coals, comprising so large a part of the national fuel reserves in the central and western states.

COAL PREPARATION

Conventional coal preparation is concerned with coal size and the separation of coal from associated mineral impurities. Coal itself

is generally regarded as a more or less uniform substance. An important concept was added to the technique of coal production, when Stopes in England called attention to the existence of the ingredient coals as distinct and separable physical entities.

With the development in recent years of special combustion equipment, particularly the underfeed domestic stoker, demands have arisen for specially prepared fuel requiring discriminating methods of preparation. Primarily, this has been a matter of size control, but occasionally special devices are installed to remove fusain from the small sizes of coal, and special means have in some cases been taken to improve the character of the coal by changing the physical constitution. Dr. L. C. McCabe in an accompanying paper of this series explains more fully some of the activities of the Illinois State Geological Survey resulting from a knowledge of the variations in the physical constitution of coal.

COAL PROCESSING

Coal processing includes all treatment of coal for commercial use whereby its character is modified by heat, pressure, or chemical means. In this category are the familiar procedures of carbonization, briquetting, and hydrogenation.

Carbonization.—Studies, explained in some detail by G. C. Sprunk, have been made by the United States Bureau of Mines,[68] which demonstrate that there is considerable difference in the coking properties of coal because of variation in type. As far as is known by the writer, no commercial scale attempt has been made to modify the type of coal used by selective preparation, except that possibly certain parts or benches of a coal bed may be selected or rejected.

Briquetting.—The briquetting properties of the coal ingredients obtained by hand picking have been investigated by R. J. Piersol[69] of the Illinois State Geological Survey. The best briquets were made from clarain, which approximated the character of the face sample of the whole coal. Pure vitrain made a poor briquet, and briquets

[68] Fieldner *et al., op. cit.*

[69] "Briquetting Illinois Coal without a Binder by Compression and Impact: Preliminary Report of a Laboratory Investigation," *Ill. State Geol. Surv. Rept. Inv. No. 31* (1932); "Briquetting Illinois Coal without a Binder: Second Report of a Laboratory Investigation," *Ill. State Geol. Surv. Rept. Inv. No. 36* (1935).

made from durain were somewhat less durable than those made from clarain. Fusain will not make a briquet when pure; it can be added to other coal up to 20 or 25 per cent, however, and the coal will still produce a satisfactory briquet, which, it is claimed, has a considerably reduced tendency to smoke.

Hydrogenation.—Investigations of the comparative usefulness of the coal ingredients for hydrogenation have been carried on by the United States Bureau of Mines[70] and will be discussed by Mr. Sprunk in another paper. The results of these investigations make it appear probable that, if the hydrogenation of coal eventually becomes an important means of producing motor fuel and oil in this country, the largest possible yield from subbituminous and bituminous coals can be obtained only by the selection and concentration of certain physical components of the coal.

CONCLUSION

One cannot expect to find in a threshold science such as this the universal agreement in theory, definitions, objectives, and practice characteristic of sciences that have long since passed the threshold, explored the interior, settled into complacent domesticity, and even worn holes in the carpet. For too long the traditional point of view has dominated the academic viewpoint toward the caustobioliths. This traditional point of view regards coal almost entirely as a problem in geological history, with interest mainly directed toward achieving a complete understanding of the origin of coal beds. Even in this field the problem of the origin and nature of coal itself is usually neglected. This abstract conventional consideration of coal is likely to give little attention to the possible relationship between the visible, but largely ignored, physical heterogeneity of the medium- and lower-rank coals and the problems of coal preparation and utilization.

[70] C. H. Fisher *et al.*, "Hydrogenation of the Banded Constituents of Coal: Fusain," *Indust. Eng. Chem.*, Vol. XXXI (1939), pp. 190–95; "Hydrogenation of Cannel Coals and Their Petrographic Constituents," *Fuel in Sci. and Pract.*, Vol. XIX (1940), pp. 84–89; "Hydrogenation of Anthraxylon (Vitrain) from Peat, Brown Coal, Lignite, Subbituminous Coal, Bituminous Coal, and Anthracite," *ibid.*, pp. 132–33; "Hydrogenation of the Banded Constituents of Coal: Attrital Matter and Anthraxylon," *Indust. Eng. Chem.*, Vol. XXXI (1939), pp. 1155–61.

RELATION OF THE PHYSICAL CONSTITUTION OF COAL TO ITS CHEMICAL CHARACTERISTICS[1]

H. H. LOWRY
Carnegie Institute of Technology

ABSTRACT

The paper is mainly a review of published data on the chemical nature of the banded contituents of coal seams. Consideration is given to ultimate and proximate composition and to the nature of the products obtained by oxidation, reduction, and thermal decomposition. In general, the petrographic components of a coal from a given seam differ in chemical composition, but the differences are not quantitatively or qualitatively constant when coals from various seams are compared. The inconsistencies in results reported are attributed, in part, to difficulty in obtaining "pure" petrographic components and in expressing the petrographic composition quantitatively. Essentially distinct types of chemical compounds peculiar to the ingredients of banded coal have not been found.

INTRODUCTION

Probably the first criterion used for classification of natural materials was appearance. Iron was iron, brass was brass, coal was coal, and gold was gold. The criterion of appearance for acceptance of a gold crown did not satisfy King Hieros in the third century B.C. and led to the discovery of Archimedes' principle—a physical test. Chemical tests were developed much later. Coals are normally banded, and the banded structure was probably accepted as just as characteristic of coal as are stripes characteristic of a zebra. It may not have been until 1859 that inherent differences between the bands were recognized, but in that year J. W. Dawson[2] considered the macroscopic constituents of normal banded coals as separate entities. Later, in 1881, F. Muck[3] recognized also that *Glanzkohle*, *Mattkohle*, and *Faserkohle* should be treated as distinctly different coal components. These terms and their general English equivalents—"bright coal," "dull coal," and "mineral charcoal" or, more recently, "fusain"—have now long been used by coal technologists.

[1] Address delivered at the Fiftieth Anniversary Celebration of the University of Chicago, September, 1941.

[2] "On the Vegetable Structures in Coal," *Quart. Jour. Geol. Soc. London*, Vol. XV (1859), pp. 626–41.

[3] "Grundzüge und Zeile der Steinkohlen Chemie" (Bonn: Strauss, 1881).

The work of M. C. Stopes in 1919[4] and of R. Thiessen in 1920[5] stimulated closer examination of these constituents and added new terminologies which, however, have not yet been accepted universally. Further interest in the differences, both chemical and functional, of these constituents—commonly known as "petrographic constituents"—resulted from the development of mechanical means for commercial separation or concentration of them for special uses.[6]

Microscopic techniques, including thin sections and relief polishing and etching, have added new distinguishing microscopic characteristics to the previously recognized macroscopic characteristics of the petrographic constituents. In effect, however, these techniques only furnish means for more completely defining the *appearance* of samples of coal. To the chemist, who is familiar with allotropic forms of elements and compounds, appearance is not a satisfactory criterion of different chemical composition or behavior in such complex chemical reactions as coals are subjected to in use. There is much evidence that differences in chemical analysis may be associated with the differences in appearance that characterize the petrographic constituents of a coal from a given seam. However, no exact correlation has yet been made, and may never be made, between the chemistry and the petrography of coal—a statement which is not meant to belittle either science.

The present gap, or perhaps gulf, between these two sciences may be attributed to many causes. There may be mentioned, first, the inadequacy of chemistry today to determine complete chemical structures for objects so large relative to the atom as are the smallest ones in coal still capable of resolution by the microscope. When such objects, different as they may appear to be optically, are subjected to the drastic chemical degradation reactions necessary for

[4] "Studies in the Composition of Coal, No. 1. The Four Visible Ingredients in Banded Bituminous Coal," *Proc. Roy. Soc. London*, Vol. XC, B (1919), pp. 470–87.

[5] "Compilation and Constitution of Bituminous Coal," *Jour. Geol.*, Vol. XXXVIII (1920), pp. 185–209; "Structure in Paleozoic Bituminous Coals," *U.S. Bur. Mines Bull. 117* (1920).

[6] K. Lehmann and E. Hoffmann, "Kohlenaufbereitung nach petrographischen Gesichtspunkten" *Glückauf*, Vol. LXVII (1931), pp. 1–14; "Application of Petrography to Coal Preparation," *Proc. 3d Internat. Conf. Bituminous Coal*, Vol. II (1931), pp. 679–700.

precise chemical definition, the apparent differences may not be and, as will be shown later, are not found.

There are inadequacies also in the development of coal petrography. The lack of agreement among coal petrographers and coal chemists in regard to equivalence of terminologies is gradually being resolved.[7] However, the advantages to be expected from strict agreement will accrue only in the future. At present the data in the literature reported by different investigators cannot be assumed to be on a common basis for comparison. Furthermore, the petrographic constituents are often intimately intermixed, and complete separation may be impossible. The petrographic purity is seldom stated and, when stated, has an indeterminate significance, for no study has yet been reported on either the precision or the accuracy of a petrographic analysis.

In considering the conclusions to be presented in this paper, the limitations mentioned in the preceding paragraphs should be clearly recognized. The data summarized in this paper have been reported mainly by British, German, and American investigators. It has been assumed that vitrain, vitrit, *Glanzkohle*, and anthraxylon are all "bright" coals and that durain, durit, *Mattkohle*, and splint are all "dull" coals. No data will be given on clarains, which, in general, appear intermediate chemically between the bright and the dull bands of a given seam. The chemical nature of "fusain," a term which is used by all investigators, will not be considered except in those cases where comparable data are given on either or both the bright and the dull coal from the same seam.

ULTIMATE AND PROXIMATE COMPOSITIONS OF ASSOCIATED PETROGRAPHIC CONSTITUENTS

While books on the chemistry of coal have generally mentioned the petrographic heterogeneity of coals, chemical differences between the associated constituents, except fusain, have evidently not been considered sufficiently regular to warrant much discussion. W. Fuchs,[8] in discussing comparative analyses published prior to 1931,

[7] E. Hoffmann, "Zweckmassigkeit der Kohlenpetrographischen-Nomenklatur," *Compt. rend. dieux. congr. l'avance. études strat. Carbonifere, Heerlen, 1935*, Vol. I (1937), pp. 313–25.

[8] *Die Chemie der Kohle* (Berlin: Julius Springer, 1931), pp. 283–88.

pointed out that some of the analyses were inconsistent, since the sums of the weighted percentages of the elements in the components did not equal the percentage in the original coal and attributed this inconsistency to the corrections used to convert the data to an ash-free basis. This question of correction for ash is particularly important, since, in general, the ash content of the bright coal is considerably less than that of the associated dull coal and fusain. However, in the present summary of the results obtained by many investigators[9] the analyses are all considered on the dry, ash-free basis as reported in the original references.

[9] A. Baranov and W. Francis, "Banded Bituminous Coal," *Fuel*, Vol. I (1922), pp. 219–22; M. C. Stopes and R. V. Wheeler, "Spontaneous Combustion of Coal in Relation to Its Composition and Structure, II," *Fuel*, Vol. II (1923), pp. 83–92; F. Foerster and R. Hünerbein, "Weitere Beiträge zur Kenntnis der sächsischen Steinkohlen," *Brennstoff-Chem.*, Vol. IV (1923), pp. 369–72; H. Winter, "Composition of Banded Bituminous Coals," *Fuel*, Vol. III (1924), pp. 134–39; A. V. Hendrickson, "Data Relating to the Banded Constituents of Bituminous Coal," *Fuel*, Vol. IV (1925), pp. 83–86; M. de Booseré, "Macroscopic Constituents of Campine Coals," *Fuel*, Vol. V (1926), pp. 522–27; W. Rittmeister, "Eigenschaften und Gefügebestandteile der Ruhrkohlen," *Glückauf*, Vol. LXIV (1928), pp. 589–94, 624–36; Dept. Sci. Ind. Research (Brit.), *Fuel Research, Phys. & Chem. Survey, No. 13*, "The Parkgate Seam" (1929); *No. 18*, "The Barnsley Seam" (1931); *No. 20*, "The Silkstone Seam" (1931); R. Holroyd and R. V. Wheeler, "The Primary Thermal Decomposition of Coal," *Fuel*, Vol. IX (1930), pp. 104–14; E. S. Grumell, "Classification of British Coals," *Proc. 3d Internat. Conf. Bituminous Coal*, Vol. II (1931), pp. 850–77; H. G. Turner and H. V. Anderson, "A Microscopical and X-Ray Study of Pennsylvania Anthracite," *Fuel*, Vol. XI (1932), 262–66; W. E. Bakes, "The Action of Solvents on Coal," *Fuel Research, Tech. Paper 37*, Dept. Sci. Ind. Research (Brit.) (1933); K. Drees and G. Kowalski, "Glanz- und Matt-Kohlen oberschlesischer Flöze, I und II," *Brennstoff-Chem.*, Vol. XV (1934), pp. 221–29, 261–66; G. Keppeler and H. Borchers, "Die Extraktion von Steinkohle und ihrer Gefügebestandteile," *Brennstoff-Chem.*, Vol. XVI (1934), pp. 341–47; A. M. Wandless and J. C. Macrae, "Banded Constituents of Coal: Interrelationships Deduced from Analytical Data," *Fuel*, Vol. XIII (1934), pp. 4–15; W. A. Bone *et al.*, "Researches on the Chemistry of Coal, VIII: The Development of Benzenoid Constitution in the Lignin-Peat-Coal Series," *Proc. Roy. Soc. London*, Vol. CXLVIII, A (1935), pp. 492–522; H. Berry and J. H. Jones, "Physical and Chemical Survey of the National Coal Resources. The Fractional Gravity Separation of the Banded Constituents of Coal," *Fuel*, Vol. XV (1936), pp. 343–51; W. A. Bone and B. J. A. Bard, "Researches on the Chemistry of Coal, VIII: Comparative Studies of the Macroconstituents of Bituminous Coals," *Proc. Roy. Soc. London*, Vol. CLXII, A (1937), pp. 495–501; C. R. Kent, "Studies in the Constitution of Coals from the Collie Field of Western Australia, III: Alkaline Permanganate Oxidations of the Coals," *Australian Chem. Inst. Jour. and Proc.*, Vol. VI (1939), pp. 207–23; C. H. Fisher *et al.*, "Hydrogenation of Spores, Resins, and Other Attrital Constituents of Coal," *Fuel*, Vol. XVIII (1939),

Certain statistical data on differences in elementary composition of bright and dull coals and fusain are given in Table 1. In all cases the figures refer to analyses of constituents from the same seam and

TABLE 1

DIFFERENCES IN ELEMENTARY COMPOSITION OF ASSOCIATED BRIGHT AND DULL COALS AND FUSAIN

	Bright-Dull	Bright-Fusain	Dull-Fusain
CARBON*			
Average difference (per cent)	−1.42 (127)†	−5.09 (70)	−3.50 (64)
Range of differences (per cent)	4.70 to −4.20	1.9 to −10.9	3.9 to −9.1
Number negative differences	119	67	60
Number positive differences	7	3	4
Number equal	1	0	0
HYDROGEN*			
Average difference (per cent)	0.24 (127)	1.72 (70)	1.46 (64)
Range of differences (per cent)	1.15 to −1.00	3.2 to 0.7	2.4 to 0.7
Number negative differences	27	0	0
Number positive differences	91	70	64
Number equal	9	0	0
NITROGEN*			
Average difference (per cent)	0.23 (67)	1.02 (18)	0.64 (13)
Range of differences (per cent)	1.08 to −0.80	1.39 to 0.05	1.07 to 0.08
Number negative differences	8	0	0
Number positive differences	57	18	13
Number equal	2	0	0
SULPHUR*			
Average difference (per cent)	0.13 (56)	−0.11 (13)	−0.26 (8)
Range of differences (per cent)	1.50 to −3.00	2.95 to −2.70	0.40 to −2.28
Number negative differences	10	3	3
Number positive differences	44	10	5
Number equal	2	0	0

* Dry, ash-free basis.

† Numbers in parentheses are total pairs of analyses.

hand-picked from the same sample of coal. Where the differences shown in the table are negative, a change of the basis of reporting

pp. 132–41; "Hydrogenation of Anthraxylon from Bituminous Coals," *Fuel*, Vol. XVIII (1939), pp. 196–203; "Hydrogenation of the Banded Constituents of Coal: Fusain," *Ind. Eng. Chem.*, Vol. XXXI (1939), pp. 190–95; G. R. Yohe and C. A. Harman, "Preparation of Humic Acids from Illinois Coals," *Trans. Illinois State Acad. Sci.*, Vol. XXXII (1939), pp. 134–46, and personal communication, 1941; G. C. Sprunk *et al.*, "Splint Coals of the Appalachian Region: Their Occurrence, Petrography, and Comparison of Chemical and Physical Properties with Associated Bright Coals," *U.S. Bur. Mines, Tech. Paper 615* (1940).

the analyses from dry, ash-free to dry, mineral matter-free would increase the differences; and where positive, a similar change would decrease the differences. Comparing bright and dull coals, the for-

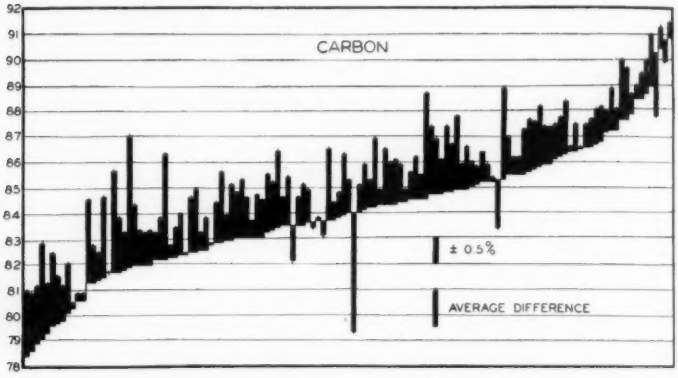


FIG. 1.—Percentage of carbon in associated bright and dull coals (dry, ash-free basis) arranged in order of increasing carbon content of the bright coals. The plain bar represents the analysis of the bright coal and the crossed bar that of the associated dull coal.

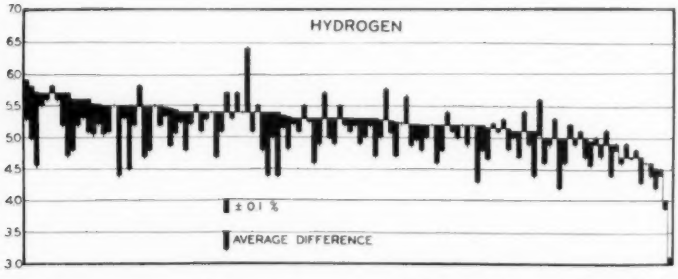


FIG. 2.—Percentage of hydrogen in associated bright and dull coals (dry, ash-free basis) arranged in order of decreasing hydrogen content of the bright coals. The plain bar represents the analysis of the bright coal and the crossed bar that of the associated dull coal.

mer have on the average lower carbon and higher hydrogen, nitrogen, and sulphur contents. Similarly, the bright coals have considerably lower carbon contents and higher hydrogen and nitrogen con-

tents than associated fusains; while the average sulphur content of the fusains is greater than that of the bright coals, ten out of thirteen samples show lower sulphur content. The differences in analyses between dull coals and associated fusains are qualitatively the same as the differences between the bright coals and fusains.

Since there is generally a greater uncertainty in clearly distinguishing the petrographic differences between bright and dull coals

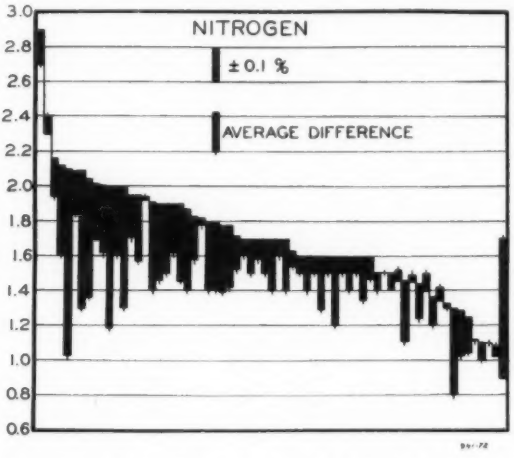


FIG. 3.—Percentage of nitrogen in associated bright and dull coals (dry, ash-free basis) arranged in order of decreasing nitrogen content of the bright coals. The plain bar represents the analysis of the bright coal and the crossed bar that of the associated dull coal.

of rank both below and above bituminous coals, the individual differences used for computing the values shown in Table 1 have been plotted in Figures 1, 2, 3, and 4. Figure 1 shows the carbon contents of the bright and dull coals arranged in order of increasing carbon content of the bright coals; the crossed bar representing the analyses of the dull coals is generally, throughout the range of carbon content from 78.3 to 90.9 per cent for the bright coals, *above* the plain bar representing the analyses of the bright coals. The first exception represents the data for a Millers Creek Seam coal[10] and would not

[10] Sprunk *et al.*, *op. cit.*

occur if the analyses were reported on a dry, mineral matter-free basis, for then the bright coal contains 83.9 and the dull coal 84.3 per cent carbon. Similarly, the next very large exception represents data for a coal from Saxony,[11] of which the dull coal contained over 50 per cent ash; if the percentage of carbon content had been reported on a dry, mineral matter-free basis, that of the dull coal would have been 87.0 per cent and that of the bright coal 84.5 per cent.[12] It

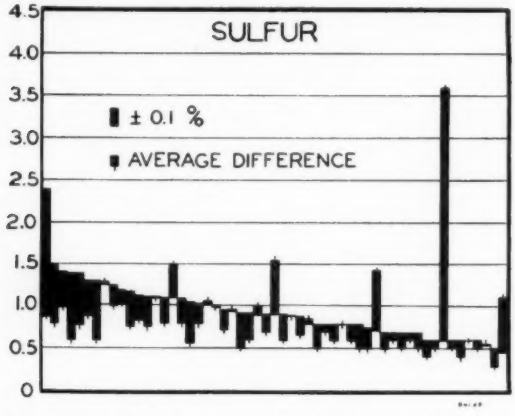


FIG. 4.—Percentage of sulphur in associated bright and dull coals (dry, ash-free basis) arranged in order of decreasing sulphur content of the bright coals. The plain bar represents the analysis of the bright coal and the crossed bar that of the associated dull coal.

thus appears likely that the carbon content on a pure coal, or dry, mineral matter-free basis, would be higher with greater consistency than on the basis usually reported. However, since the factor to be used for conversion from ash-free to mineral matter-free basis is dependent on the composition of the mineral matter, which is generally not determined, it has not appeared worth while to recompute all the data to some other arbitrary basis, although in future work this point appears to deserve consideration. Disregarding the two coals

[11] F. Foerster and R. Hünerbein, *op. cit.*

[12] In converting percentage of ash to mineral matter, it has been assumed for these calculations that mineral matter equals 1.1 ash plus 0.55 sulphur.

showing less carbon in the dull component than in the bright, where the bright coals contained more than 86 per cent carbon, the individual differences exceeded the average difference in only six cases out of twenty-two, which suggests that the differences in elementary composition of the petrographic constituents may possibly decrease with increasing rank, although the results may also be attributed to indefiniteness of the petrography of high-rank coals.

The average differences in hydrogen, nitrogen, and sulphur contents of the bright and dull components are not many times greater than the probable errors of analysis. As may be seen, however, from the individual values plotted in Figures 2, 3, and 4, significant differences may exist. The type of plot is the same as used in Figure 1.[13] The hydrogen contents are given in the order of decreasing hydrogen contents of the bright coals, and this order is *not* the same as shown in Figure 1. Dull coals contain more hydrogen than their associated bright coals much oftener than they contain less carbon, and this may be attributed to the extremely variable content of "recognizable plant entities" of the dull coals.[14] In an investigation of coals from different districts from the Upper Beeston Seam, Wandless and Macrae[15] made a distinction between black and gray durains: the average carbon and hydrogen contents of the vitrains were 84.2 and 5.2 per cent, respectively; the gray durains contained on the average 1.3 per cent less carbon and 0.4 per cent less hydrogen, while, on the other hand, the black durains contained on the average only 0.8 per cent less carbon and contained 1.0 per cent *more* hydrogen. The data for these eleven black durains are not included either in Table 1 or in Figures 1 and 2. However, since "durain" and "dull coal" are generally used more or less synonymously, it may be suspected that the dull coals which have greater hydrogen contents than their associated bright coals are "black durains" of varying degrees of

[13] For another method of plotting data on elementary composition to show differences between the associated petrographic constituents see H. Apfelbeck, "Entstehung, Veredlung und Verwertung der Kohle," (Berlin: Gebrüder Borntraeger, 1930), pp. 22–61, especially pp. 30–33 and Fig. 4.

[14] These "entities" include "hyddrogen-rich" spores, waxes, resins, and cuticles, which are generally stated to be resistant to bacterial decay, and therefore may accumulate in the coalification process.

[15] Wandless and Macrae, *op. cit.*

"blackness."[16] This point of view is not in disagreement with the position of Thiessen, who has stated[17] that "opaque attritus" is the distinguishing petrographic constituent of splint, or dull, coals: the degree of opacity is indeterminate.

The distinction between black and gray durains made by Wandless and Macrae resulted from their observation that the analyses for the durains were extremely variable and led them to a gravity separation of individual samples. Although they suggested that black durain is a normal constituent of dull coal, G. E. Foxwell[18] characterized it as a type found only in South Wales. However, the work of Berry and Jones[19] on gravity separation of each petrographic constituent from the Northumberland-Beaumont Seam appears to favor the view of Wandless and Macrae and also suggests that this method of study warrants further development for determining the chemical natures of petrographic constituents. Berry and Jones showed, for example, that a given hand-picked sample of vitrain could be separated by gravity methods into fractions ranging in carbon content from 84.4 to 85.3 per cent and in hydrogen content from 5.02 to 5.72 per cent; and, similarly, the range for durain was from 85.2 to 85.6 per cent carbon and from 5.27 to 6.87 per cent hydrogen, and for fusain from 86.6 to 89.4 per cent carbon and from 3.65 to 4.76 per cent hydrogen. They concluded that neither durain nor fusain, however carefully hand-picked, are physical or chemical entities but that vitrain appeared to approach more closely than the others to physical homogeneity. This work throws serious doubt on the value of any attempt to compare the chemical properties of the petrographic constituents as reported in the literature, since the differences between different fractions of a single petrographic constituent from a given seam may exceed those observed from the average samples of two or more ingredients.

It may be noted from Figure 2 that as the hydrogen contents of

[16] *Ibid.*

[17] Thiessen and Sprunk, "The Origin of the Finely Divided or Granular Opaque Matter in Splint Coals," *Fuel*, Vol. XV (1936), pp. 304–15.

[18] "How Far Is the Proximate Analysis a Reliable Guide to Coal Behavior?" *Jour. Inst. Fuel*, Vol. XIV (1941), pp. 190–91.

[19] Berry and Jones, *op. cit.*

the bright coals decrease, which is generally associated with an increase of rank and of carbon content, the differences in hydrogen contents of the bright coals and their associated dull coals become less definite, and here, again, this may be provisionally attributed to the inadequacy of petrographic criteria for high-rank coals.

The differences in nitrogen and sulphur contents of bright and dull coals shown in Figures 3 and 4 should probably be interpreted with reservations. Generally the significance of the nitrogen content of coals has been underestimated. Biological processes in coal formation are admitted almost universally: bacteria contain nitrogen and have been postulated as the source of nitrogen in coal.[20] The lower nitrogen content of dull coals might, therefore, be attributed to cessation of biological decay earlier in the case of coalification of dull coals than of bright coals. Sulphur also is an element associated with protein material such as might be expected in residues from bacterial action. However, the sulphur in coal may be either organic or inorganic. It is generally assumed that the inorganic-pyritic-sulphur is adventitious in origin. From Figure 4 it may be seen that in a very few cases the sulphur contents of the dull coals are very much greater than those of the associated bright coals; although without specific confirmation from the reporters of the data, it may provisionally be assumed that the cases of high sulphur content of the dull coals are the result of contamination of the organic matter with infiltrated pyrites.

No detailed consideration has been given to the differences in oxygen contents of the petrographic constituents, since oxygen is not directly determined by analysis and the values reported include a summation of the errors of analysis for the other elements. The data in Table 1, however, permit a calculation which shows that on the average bright coals contain about 0.8 per cent more oxygen than associated dull coals and about 2.5 per cent more than associated fusains, and dull coals about 1.7 per cent more than associated fusains.

The differences in proximate analysis of associated petrographic constituents are even less regular than those in elementary analysis

[20] E. Terres, "Contributions to the Origin of Coal and Petrography," *Proc. 3d Internat. Conf. Bituminous Coal*, Vol. II (1931), pp. 797–808.

and only very general conclusions seem warranted. In the great majority of cases[21] the moisture content of bright coals is greater than that of the associated dull coals. The moisture contents reported for fusains show no regular trend in comparison with those for their associated petrographic constituents; this may be accounted for by the relatively marked dependence of moisture of fusains on the percentage of saturation of the atmosphere between 90 and 100 per cent.[22]

Although there are frequent exceptions, in general the ash contents increase in the order bright coal, dull coal, and fusain.[23] Lessing[24] reported complete analyses of ashes from the banded constituents of the Homestead Thick Seam and concluded that the ash from the bright coal represented the original plant ash, that from the dull coal was derived mainly from clay, and that much of the ash in the fusain came from infiltration. The softening temperature of the ash from dull coals is quite generally higher than that from the associated bright coals.[25]

As Grumell has concluded from the examination of many data,[26] the volatile matter content of bright coals relative to associated dull coals is indefinite though more often higher, which is in agreement with other investigations.[27] However, Hoffmann found for twelve Saar coals that the volatile matter content of the dull coals was always greater than that of the associated bright coals and in the low-rank coals as much as 20 per cent greater.[28] This apparent disagree-

[21] Grumell, *op. cit.;* Wandless and Macrae, *op. cit.;* Sprunk *et al.*, *op. cit.;* O. W. Rees *et al.*, "Moisture Relations of Banded Ingredients in an Illinois Coal," *Ind. Eng. Chem.*, Vol. XXXIII (1941), pp. 416–19.

[22] Rees *et al.*, *op. cit.*

[23] Grumell, *op. cit.;* Wandless and Macrae, *op. cit.;* Sprunk *et al.*, *op. cit.;* R. Lessing, "Coal Ash and Clean Coal," *Jour. Soc. Arts*, Vol. LXXIV (1926), pp. 205–18, 224–41; *Fuel*, Vol. V (1926), pp. 17–23, 69–76, 117–24.

[24] *Op. cit.*

[25] Grumell, *op. cit.;* Sprunk *et al.*, *op. cit.*

[26] Grumell, *op. cit.*

[27] Sprunk *et al.*, *op. cit.;* L. L. Fermor, "On the Specific Gravity and Proximate Composition of Some Indian Durains," *Fuel*, Vol. X (1931), pp. 35–43.

[28] H. Hoffmann, "Die makroskopischen Gemengteile der Saarkohle," *Glückauf*, Vol. LXIV (1928), pp. 1237–43, 1273–80; "The Macroscopic Constituents of Saar Coking Coal," *Fuel*, Vol. VIII (1929), pp. 525–41.

ment may well be attributed to the heterogeneous nature of dull coals as previously discussed, particularly since Wandless and Macrae also found that in all eleven cases the black durains had almost 50 per cent greater volatile matter contents, and the gray durains in seven out of nine cases had somewhat lower volatile matter contents, than the associated vitrains.[29]

The calorific value of dull coals is generally higher than that of the associated bright coals.[30] This would be expected from the preceding discussion on elementary composition, since on the average dull coals contain only slightly less hydrogen and considerably more carbon and less oxygen than do the bright coals.

Seyler has proposed an interesting, provocative, and suggestive method of correlation of chemical and petrographic analyses of coals which uses both proximate and ultimate chemical analyses.[31] In fact, the method might be said to be one for determining petrographic composition from the hydrogen content and volatile matter content of a sample of coal. From consideration of a large amount of analytical data on the petrographic constituents of coals, Seyler concluded that coals are composed of three components: (1) vitrinite, (2) exinite, and (3) fusinite. Vitrinite is the characteristic component of vitrain, fusinite of fusain, and exinite represents spore-exines and cuticles. It is somewhat difficult to separate a priori assumption and conclusion from experimental data in Seyler's presentation, but it appears that the method was, in part, derived as follows.

Several vitrains, which showed on microscopic investigation no trace of other petrographic constituent, were analyzed. The analyses were corrected to $C + H + O + N = 100$, where $N = 1$, using Parr's formula with a correction for carbonates. All sulphur, both mineral and organic, was eliminated. The volatile matter contents of these vitrains could then be calculated from the equation

$$V_u = 10.61H - 1.24C + 84.15 . \qquad (1)$$

[29] Wandless and Macrae, *op. cit.*

[30] Grumell, *op. cit.*; Sprunk *et al.*, *op. cit.*

[31] C. A. Seyler, "Petrology and the Classification of Coal, I and II," *Colliery Guardian*, Vol. CLV (1937), pp. 990–94, 1046–48, 1087–89, 1137–39, 1231–33; *Proc. So. Wales Inst. Engrs.*, Vol. LIII (1938), pp. 254–327, 396–407.

When this equation was then used for the other petrographic constituents, the calculated volatile matter, V_u, was always less than the observed V, so that

$$V = V_u + \Delta V , \qquad (2)$$

and the correction term, ΔV, was called the volatile displacement. It is important to note that the V_u in equation (2) is not the volatile matter content of vitrain associated with the particular petrographic constituent but is the volatile matter content a vitrain would have if it had the composition of the component under consideration. The volatile displacement of all vitrains, if they were pure vitrinite, would be zero. It then appears that Seyler assumed that the percentage of hydrogen contained by vitrinites is 5.25. Also, it appears that, from the analyses of fusains free from exinite, he assumed all fusinites in all coals from the bituminous rank to anthracites—but not including anthracite—contained 2.23 per cent hydrogen and had a volatile displacement of 15.45 per cent. Then, if the hydrogen content and volatile displacement of a fusain are known, its composition may be determined from a plot such as is shown in Figure 5, in which actual data for seven fusains are given.

Now, it was assumed that all coals are three-component systems, so if the hydrogen content and volatile displacement of the third component, exinite, were known, the triangular diagram could be completed as shown in Figure 5. The locus of the previously undetermined apex was obtained from examination of data on separated plant remains of the Upper Beeston Seam.[32] It was pointed out that the locus of this point varies over a wide range for coals from different seams; for instance, for twelve coals from the Saar the hydrogen contents of the exinites ranged from 7.88 to 12.28 per cent and the volatile displacements from 3.51 to 11.44 per cent. However, if the hydrogen content and volatile displacement of the exinite from a given seam were known and assumed constant for the seam, all coals from the seam must lie within the triangle, whether vitrains, clarains, durains, fusains, or mixtures.

How well Seyler's conclusions are justified by existing data is

[32] Wandless and Macrae, *op. cit.*

shown in Figure 6, redrawn from his Figure 10, for coals from the Upper Beeston Seam.[33] It is evident that the vitrains, gray durains, black durains, and fusains fall in different areas of this triangular plot. From the position on the diagram, the petrographic composition can readily be determined. For the so-called "black durains," the range in composition is very great: vitrinite from about 9 to 64

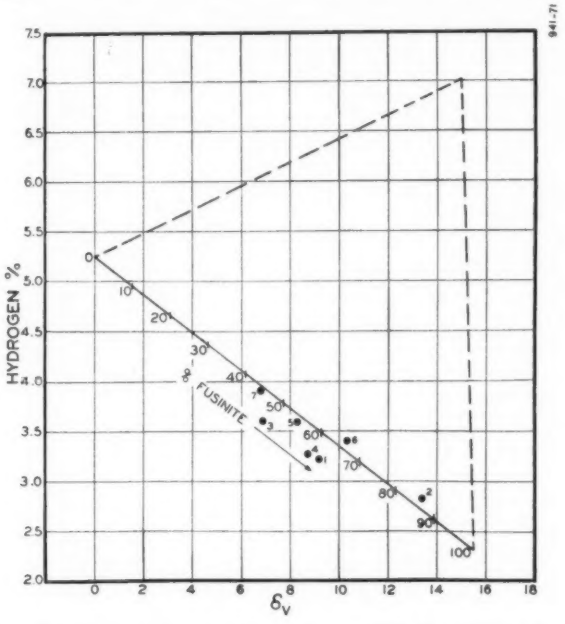


FIG. 5.—Percentage of hydrogen plotted against volatile displacement, δ_V, for seven fusains, after Seyler ("Petrology and the Classification of Coal," *op. cit.*).

per cent, fusinite from 3 to 25 per cent, and exinite from 34 to 71 per cent. This variation is in accord with and an explanation of the fact that differences in chemical composition of durains (dull coals) and their associated vitrains (bright coals) are not constant even for coals from a given seam.

So far as is known, this method of Seyler's of describing coals has

[33] *Ibid.*

not been used by anyone else nor has the micropetrological (Seyler) composition of any given series of coals so determined been correlated with the chemical reactions of the coals. If one could accept the validity of Seyler's assumptions, this would be relatively simple, since construction of the diagram would require only the isolation of the pure exinite characteristic of the seam and determination of

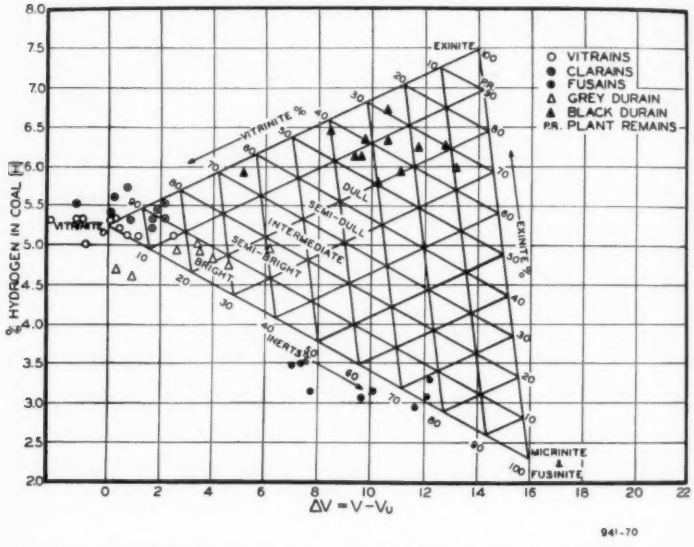


FIG. 6.—Plot of hydrogen content against volatile displacement, ΔV, for petrographic constituents of the Upper Beeston Seam according to Seyler's classification. (Redrawn from Fig. 10 of Seyler, *op. cit.*)

its hydrogen content and volatile displacement. However, as Seyler cautions, the analyses must be accurate, since an error of only 0.1 per cent in hydrogen content may cause an error of about 10 per cent in petrographic composition when determined graphically from the diagram.

The quantitative aspects of Seyler's procedure are particularly attractive from a chemist's point of view. That the petrographic composition is determined by analytical procedures with which he is

familiar is a source of confidence. The results which he has presented suggest that the reason for apparent irregularities, and even contradictions, in the literature concerning the chemical analyses and behavior of bright and dull coals—vitrain, clarain, durain, and fusain—may be attributed to inadequacies in usual petrographic distinctions. The results also seem to offer a challenge: Will the tools of the chemist or those of the petrographer determine the petrographic composition of a coal? The result also suggests that, if petrographic constitution per se has a determining effect on the behavior of coal in use, correlation with either proximate or ultimate analysis is not to be expected; both are required in the hydrogen content and the volatile displacement.

CHEMICAL NATURE OF THE PETROGRAPHIC CONSTITUENTS

As stated in an earlier paragraph, a complete definition of the chemistry of coal is not possible at present. The following discussion is based on the point of view that coals are natural polymers[34] and that the average size of the polymeric unit increases with the rank of the coal.[35] The tools available to the chemist for determining the chemical nature are limited: most information has been obtained from studies of (1) thermal decomposition in the presence of a solvent, or (2) in its absence, or (3) from oxidation or (4) from reduction reactions. These will be considered in turn.

It is trite to say that chemical properties are related to chemical composition. However, in considering the differences in the chemical natures of the petrographic constituents, this is a serious complicating factor. As shown previously, the chemical compositions of these constituents vary. This necessitates a decision in regard to the question of whether the differences in the chemical nature of the petrographic constituents are a result of differences in chemical composition or of differences in petrography. The answer is not unequivocal.

[34] H. C. Howard, "The Polymeric Character of a Bituminous Coal," *Jour. Phys. Chem.*, Vol. XL (1936), pp. 1103–12.

[35] H. H. Lowry, "The Coal Research Laboratory of the Carnegie Institute of Technology," *Jour. Inst. Fuel*, Vol. X (1937), pp. 291–301; B. Juettner, "The Nature of Carbonaceous Materials as Revealed by the Yield of Mellitic Acid," *Jour. Amer. Chem. Soc.*, Vol. LIX (1937), pp. 1472–74.

SOLVENT ANALYSIS

It has long been assumed that the action of solvents on coals could be used as a significant distinction. Certain recent work has indicated that, in their action on coal, solvents are primarily depolymerizing agents.[36] One of the most frequently used solvent analyses is that proposed by A. H. Clark and R. V. Wheeler,[37] in which coal is extracted with pyridine at its normal boiling-point and the extract resolved with chloroform or other solvents. In the case of sixteen coals,[38] of which the carbon content of the bright coals ranged from 78.32 to 87.7 per cent, averaging 82.34 per cent, the pyridine extract of the bright coals ranged from 12.8 to 34.2 per cent and averaged 19.29 per cent, while that of the dull coals ranged from 3.9 to 21.6 per cent and averaged 10.29 per cent. In general, the percentage soluble in pyridine decreased with the increase in carbon content of the coal, but also the amount extracted by pyridine for a given carbon content of the coal was greater for bright coals than for dull coals. On the average, about twice as much of the substance of bright coals was depolymerized by pyridine as was the case for dull coals. Also, the amount soluble in both pyridine and chloroform, 3.6–20.3 per cent, averaging 6.93 per cent, was considerably greater in the case of the bright coals than in that of the dull coals, for which the amount ranged from 3.1 to 8.6 per cent and averaged 4.93.

The data available for comparison of bright coals, or dull coals, with their associated fusains, are extremely limited.[39] It may be said, however, that the amount soluble in pyridine and the fraction

[36] R. S. Asbury, "Action of Solvents on Coal: Extraction of Edenborn Coal at Elevated Temperatures," *Ind. Eng. Chem.*, Vol. XXVI (1934), pp. 1301–6; "Action of Solvents on Coal: Extraction of a Pittsburgh Seam Coal with Aniline, Tetralin and Phenol at Elevated Temperatures," *ibid.*, Vol. XXVIII (1936), pp. 687–90; M. W. Kiebler, "Extraction of a Bituminous Coal: Influence of the Nature of Solvents," *Ind. Eng. Chem.*, Vol. XXXII (1940), pp. 1389–94; B. S. Biggs, "The Chemical Nature of Extracts from a Bituminous Coal," *Jour. Amer. Chem. Soc.*, Vol. LVIII (1936), pp. 484–87.

[37] "The Volatile Constituents of Coal, Part III," *Trans. Chem. Soc.*, Vol. CIII (1913), pp. 1704–15.

[38] Baranov and Francis, *op. cit.;* Stopes and Wheeler, *op. cit.;* de Booseré, *op. cit.;* Holroyd and Wheeler, *op. cit.;* Bakes, *op. cit.;* Drees and Kowalski, *op. cit.*

[39] De Booseré, *op. cit.*

of the pyridine soluble material also soluble in chloroform are definitely less for fusains than for dull coals.

Other solvents in general yield less extract from dull coal than from the associated bright coals[40] and still less from the fusains.[41] In a few cases, however, benzene at about 280° C. has been reported to give a larger extract from the dull component.[42] W. A. Bone and B. J. A. Bard,[43] from a study of the bright and dull fractions of coals from the Busty Seam and from the Dalton Main Seam, concluded that there was no material difference either in yield or in ultimate composition of the extracts obtained with benzene at 280° C.

Chemically, these data on the action of solvents on coal may be interpreted to signify that bright coals are in general more readily depolymerized than the associated dull coal and that a greater proportion of the depolymerized units of the bright coals is, as a rule, of lower molecular weight than in the case of their associated dull coals.

THERMAL DECOMPOSITION

Most of the studies on thermal decomposition of the petrographic constituents of coal have been primarily concerned with carbonization, a subject which will be treated by another author in this series. F. V. Tideswell and R. V. Wheeler[44] included decomposition in vacuum as a method for characterizing the components of coal and concluded:

> The general impression created is of a gradation of properties as we pass from vitrain to durain. Fusain stands apart. No characteristic reaction or behavior for any one of the components of banded coal such as might be expected were

[40] Drees and Kowalski, *op. cit.;* Keppeler and Borchers, *op. cit.;* F. Fischer *et al.*, "Über das Verhaltan von feinstgemahlenen Steinkohlen und ihrer Gefügebestandteile bei der Extraktion und Verschwelung," *Brennstoff-Chem.*, Vol. XIII (1932), pp. 364–70.

[41] Fischer *et al.*, *op. cit.*

[42] Drees and Kowalski, *op. cit.;* H. Broche and H. Schmitz, "Beitrag zur Frage des Backens und Blähens der Steinkohle: Die Bitumina der Gefügebestandteile Glanzkohle und Mattkohle," *Brennstoff-Chem.*, Vol. XIII (1932), pp. 81–85; "Contribution to the Problem of the Caking and Swelling of Bituminous Coal," *Fuel*, Vol. XII (1933), pp. 47–51.

[43] "Researches on the Chemistry of Coal, VIII; Comparative Studies of the Macroconstituents of Bituminous Coals," *Proc. Roy. Soc. London*, Vol. CLXII, A (1937), pp. 495–501.

[44] "Studies in the Composition of Coal: Chemical Investigation of Banded Bituminous Coal," *Jour. Chem. Soc.*, Vol. CXV (1919), pp. 619–36.

there a fundamental difference in chemical composition was disclosed. Whilst making clear interesting differences the work has not revealed the presence of essentially distinct types of chemical compounds peculiar to any of the ingredients of banded coals.

Almost the same words are used again in 1923 by Stopes and Wheeler.[45] Comparative vacuum distillation of bright and dull coals from the Hamstead and Barnsley seams in 1930, led Holroyd and Wheeler[46] to conclude that "the results so far obtained do no more than throw doubt on the identity in type of the ulmins" of the associated bright and dull components.

Hendrickson studied the decomposition at 900° C. of bright and dull coals from several seams[47] and found that the bright coals yielded the most gas, the least tar, and the most coke. However, he concluded that "similar banded constituents from different sources do not show the same characteristics, that is, do not show definite characteristics which can be regarded as peculiar to each ingredient."

In a study of eight coals from Upper Silesia, of which the bright components ranged in carbon content from 79.0 to 85.0 per cent and averaged 82.6 per cent, and the dull components ranged from 82.0 to 86.0 per cent and averaged 83.7 per cent, Drees and Kowalski[48] found that the total volatiles obtained in the Fischer Assay Test at 500° was greater for the bright coals in four cases and for the dull coals also in four cases. Water of decomposition was obtained in greater amount from the bright coals in every case, and the yield of gas was greater and of primary tar less from the bright component in six out of the eight cases. On the basis of the original coals, the yield of phenols ranged from 2.0 to 2.8 per cent and averaged 2.5 per cent for the bright coals in comparison with a range of 2.2 to 2.5 per cent and an average of 2.4 per cent for the dull coals. These facts, and others, led the authors to conclude that the dull coals contained less substance of humic origin than did the associated bright coals. From a similar study on only two coals Keppeler and Borchers[49] concluded that in chemical behavior and composition bright and dull coals show great similarity and only gradual differences, which, as

[45] *Op. cit.*
[46] *Op. cit.*
[47] *Op. cit.*
[48] *Op. cit.*
[49] *Op. cit.*

they pointed out, is difficult to bring into agreement with the idea of a great difference in the original source material.

Earlier this year the present author and his associates published a statistical study of the large amount of data secured by the United States Bureau of Mines on yields and properties of the products obtained at 100° C. intervals[50] on heating fifty-five American coals and their blends to temperatures ranging from 500° to 1100° C. Petrographic analyses were given for twenty-eight of the coals. Equations were derived by least-squares methods for correlation of the reported values with the proximate analyses of the coals, at first disregarding the petrographic analyses. This appeared justifiable, since the values calculated for the extreme petrographic types did not differ from the observed values significantly more than the average errors of the equations. However, it was also determined that a significant correlation between the deviations from the equations and the petrographic analysis existed for only a few properties at single isolated temperatures; in these cases the inclusion of the percentage bright coal as a factor in the equations gave a maximum reduction in the probable error of the calculated values of about 10 per cent. These facts may be interpreted as signifying that coal petrography is not in itself a determining factor in the course of thermal decomposition reactions of coals, though it has an indirect effect as reflected in the proximate analysis. It is recognized that this conclusion is at variance with that based on other work of the Bureau of Mines on the low-temperature assay of certain hand-picked samples of bright and dull coals.[51]

OXIDATION

There have been several investigations which show that the reactivity to oxidizing agents differs for associated banded components of coals. A. V. Hendrickson[52] measured the rate and amount of temperature rise when the bright, dull, and fusain factions of certain Somerset coals were treated with nitric acid of specific gravity 1.42.

[50] H. H. Lowry *et al.*, "Correlation of the Bureau of Mines–American Gas Association Carbonization Assay Tests with Coal Analyses," *Amer. Inst. Mining Met. Engrs., Tech. Pub. 1332* (1941).

[51] Sprunk *et al.*, *op. cit.*

[52] "Action of Nitric Acid on Coal, II," *Fuel*, Vol. II (1923), pp. 356–61.

The rate was greatest for the bright coals and least for the fusains. The temperature rise after 5 minutes ranged from 15.6 to 37.3° for the bright coals, from 15.6 to 33.3° for the dull coals, and from 15.6 to 23.5° for the fusains.[53] The percentage increases in weight were also in the same order and amounted to 28.6, 28.4, and 14.2 for the bright, dull, and fusain fractions, respectively. The differences between the bright and dull fractions do not appear significant. Advantage has been taken of the lower rate of oxidation of fusain than of its associated petrographic constituents on reaction with nitric acid to develop a chemical method for its determination,[54] which has been shown to give results in agreement with petrographic methods of analysis.[55] A less accurate, though analogous, method, using as reagent potassium chlorate dissolved in 2 to 4 N nitric acid, was proposed in 1930 by F. Heathcoat.[56]

It has been shown that, when the banded constituents of Illinois coal are subjected to dry-air oxidation at 150° C. or to air oxidation in a sodium hydroxide suspension at 95° C., the bright coal is almost completely, and the fusain almost not at all, converted to humic acids.[57] Air oxidation over a period of eight weeks at temperatures gradually increasing to 400° C. of the bright and dull coals and fusain from a Mathias Stinnes coal ground to micron size has been shown to give appreciable yields of crystalline acids.[58] The only differences noted for the behavior of the individual petrographic constituents were in the temperatures at which crystal formation began and the quantity of sublimate obtained.

[53] D. J. W. Kreulen, "Über die bei der Behandlung verscheidener Steinkohlenarten mitt konzentrierter Schwefelsäure und Saltpetersäure freiwerdenden Wärmemengen," *Brenstoff-Chem.*, Vol. XI (1930), pp. 41–43.

[54] W. Fuchs *et al.*, "The Chemistry of the Petrographic Constituents of Bituminous Coal, I. Studies on Fusain," *Penn. State Coll., Mineral Ind. Exper. Stat. Bull. 23* (1938).

[55] R. Belcher and A. L. Godbert, "The Rational Analysis of Coals, I. The Determination of Fusain Content," *Fuel*, Vol. XVIII (1939), pp. 270–74; B. C. Parks *et al.*, "Determining Fusain Content of Illinois Coals," *Ind. Eng. Chem., Anal. Ed.*, Vol. XIV (1942), pp. 303–5.

[56] "Determination of Fusain," *Fuel*, Vol. IX (1930), pp. 452–58.

[57] Yohe and Harman, *op. cit.*

[58] F. Fischer *et al.*, "Über die Bildung krystallisierter Oxydationsprodukte beim Erhitzen von Brennstoffen im Luftstrom. III. Mitteilung über μ-Kohlen," *Brennstoff-Chem.*, Vol. XIV (1933), pp. 184–87.

The amount of permanganate reduced by coals in alkaline medium under specified conditions[59] has been used to differentiate coals. Drees and Kowalski[60] determined the permanganate numbers of the bright and dull components of eight Upper Silesian coals and also of the residues resulting from their extraction with pyridine at its normal boiling-point for eight hours. As a rule the permanganate number is lower the higher the rank of the coal. However, although the

TABLE 2

COMPARATIVE ALKALINE PERMANGANATE OXIDATIONS OF ASSOCIATED BRIGHT AND DULL COALS (IN PERCENTAGES)

	Barnsley Seam*		Busty Seam†		Dalton Main Seam†		Mitchell Main Seam†	
	Bright	Dull	Bright	Dull	Bright	Dull	Bright	Dull
Carbon	82.4	84.6	85.85	86.90	84.70	86.45	86.30	88.85
Hydrogen	4.8	4.9	4.60	4.65	5.70	5.20	5.80	5.20
Percentage of carbon appearing as:								
CO_2	40.8	37.6	35.9	38.8	40.0	39.2	40.0	39.2
Acetic acid	2.0	1.7	1.6	1.4	1.9	2.0	1.7	1.6
Oxalic acid	14.2	12.9	12.9	10.9	15.1	11.9	15.9	12.1
Benzenoid acids	39.0	43.9	46.7	47.8	39.9	45.1	41.0	46.0
Total	96.0	96.1	97.1	98.9	96.9	98.2	98.6	98.9
Hours required for oxidation	.....	.....	26	172	21	29	45	50
Ratio $KMnO_4$ to coal used	10.9	10.9	9.3	10.0	9.7	9.9	11.0	10.7

* Bone *et al.*, *op. cit.* † Bone and Bard, *op. cit.*

dull coals in general were higher in carbon content, or "rank," in every case their permanganate numbers were higher than those of the associated bright coals, averaging about 12 per cent higher. The same regularity did not exist on comparison of the residues from the pyridine extraction. It was suspected that the results were in part

[59] In this case, the permanganate number was expressed as the cubic centimeters of 0.1 N $KMnO_4$, reduced by 0.5 gm. of coal ground to less than 0.2 mm. size when the reaction was carried out for 2 hours at 75° C. between 0.5 gm. of coal and 200 cc. of 0.1 N $KMnO_4$ and of 50 cc. of 0.1 N NaOH.

[60] *Op. cit.*

due to differences in size distribution of the two components, but this was proven not to be the case.

When coal is oxidized with alkaline permanganate at its boiling-point for long periods of time, the carbon of the coal is completely converted to organic acids, and the distribution between the various acids has been used by Bone and co-workers to compare fundamental structures of coals of different rank and type. Results obtained in comparative studies of associated bright and dull coals[61] are given

TABLE 3

COMPARATIVE ALKALINE PERMANGANATE OXIDATIONS OF ASSOCIATED BRIGHT COALS AND FUSAINS (IN PERCENTAGES)

	Busty Seam*		Dalton Main Seam*		Proprietary Seam†	
	Bright	Fusain	Bright	Fusain	Bright	Fusain
Carbon	85.85	89.60	84.70	88.90	76.1	78.6
Hydrogen	4.60	4.65	5.70	5.20	4.65	3.55
Percentage of carbon unchanged	.....	50.9	.....	50.2	.....	.....
Percentage of carbon reacted appearing as:						
CO_2	35.9	45.3	40.0	47.4	46.9	39.8
Acetic acid	1.6	1.4	1.9	1.0	1.4	0.2
Oxalic acid	12.9	10.3	15.1	7.7	9.9	5.6
Benzenoid acids	46.7	41.6	39.9	42.4	40.8	53.5
Total	97.1	98.6	96.9	98.5	99.0	99.1
Hours required for oxidation	26	192	21	160	.....	.....
Ratio $KMnO_4$ to coal used	9.3	.....	9.7	.....	10.7	9.5

* Bone and Bard, *op. cit.* † Kent, *op. cit.*

in Table 2 and in similar studies of associated bright coals and fusains[62] are given in Table 3. It is doubtful that the differences in distribution of the carbon of the coal among the reaction products are very significant, but the lower reactivity of the dull coal indicated by the increase in hours required for oxidation is in accord with other observations.[63] The resistance to oxidation of the fusains was even

[61] Bone *et al.*, *op. cit.*; Bone and Bard, *op. cit.*

[62] Bone and Bard, *op. cit.*; Kent, *op. cit.*

[63] M. Gauzelin and L. Crussard, *Rev. ind. minerale No. 398* (1937), pp. 373–402; "Studies of the Reactivity of Coal with Permanganate," *Fuel*, Vol. XVII (1938), pp. 36–40.

more marked, only about half of their carbon being converted to acidic products in the time allowed. This latter point raises the question whether or not the 50 per cent of the fusain oxidized was characteristic fusain or possibly largely other petrographic constituents intimately associated with the fusain.[64] It may be noted that the percentage yield of CO_2 from fusain was materially greater than that yielded by either of the other two constituents; it appears possible that if the oxidation of the fusain were carried to the point where all its carbon was converted to soluble products, the percentage yield of CO_2 would show still greater differences. Bone and Bard[65] concluded from their work that, "viewed as a whole, there is nothing in the evidence suggestive of more than quite minor differences between the fundamental benzenoid structures of the three principal macro-constituents of a given coal, although the dull coal appears to be rather more matured than the corresponding bright coal."

REDUCTION

The reduction reaction most frequently used in studies of coal is hydrogenation. There is very little work described in the literature that has employed this reaction for studying possible differences in the chemical natures of the petrographic constituents of coals. The work of the Bureau of Mines[66] has included a determination of the amenability of the associated components for raw materials in the hydrogenation process, and the papers cited include references to prior work on this subject. Some of the data of these workers[67] are shown in Table 4, from which it is clear that the completeness of conversion is greatest for the bright coals and least for the fusains—the same order of reactivity noted in other reactions. In the original papers it was stated that the bright coal (anthraxylon) was free from other components, that the dull coal was a mixture primarily of translucent and opaque attritus (the proportions being given), and that the fusains behaved as though they were mixtures. An examination of the data on composition of the products obtained has shown no distinctive chemical differences between those from the various banded components. This is in accord with other work which included a detailed chemical study of the products obtained in com-

[64] Seyler, *op. cit.*

[65] Bone and Bard, *op. cit.*

[66] C. H. Fisher *et al.*, *op. cit.*

[67] *Ibid.*

parative hydrogenations of a predominantly bright Pittsburgh Seam coal (carbon = 85.0 per cent) and a predominantly dull High Splint Seam coal (carbon = 83.8 per cent) which showed that the materials from both were of similar chemical nature.[68]

TABLE 4

COMPARATIVE LIQUEFACTION DATA ON ASSOCIATED PETROGRAPHIC CONSTITUENTS OF SEVERAL AMERICAN COALS*

(DRY, ASH-FREE BASIS)

	Bright (Per Cent)	Dull (Per Cent)	Fusain (Per Cent)
Carbon	83.5	85.4	.....
Hydrogen	5.7	4.7	.....
Conversion	90.4	59.8	.....
Carbon	84.5	85.6	92.6
Hydrogen	5.5	5.3	2.8
Conversion	98.3	85.6	15.1
Carbon	85.3	.....	92.6
Hydrogen	5.4	.....	3.0
Conversion	97.8	.....	19.5
Carbon	86.1	87.5	92.0
Hydrogen	5.3	5.5	3.3
Conversion	95.8	75.7	15.7
Carbon	89.9	.....	93.5
Hydrogen	4.8	.....	3.3
Conversion	95.4	.....	10.4

* Fisher *et al.*, *op. cit.*

MISCELLANEOUS REACTIONS

Although little difference was found at 10–100° C. in the oxygen adsorption of the bright and associated dull coals from the Hamstead Seam,[69] the fusain adsorbed much greater amounts and at higher rates at 10° and 50° C. but not at 100° C. It appears probable that the low-temperature phenomena may be attributed to physical factors such as particle size and porosity and that the rela-

[68] C. D. LeClaire, "Nature of Oils Obtained from the Hydrogenation of a Few Typical Bituminous Coals," *Jour. Amer. Chem. Soc.*, Vol. LXIII (1941), pp. 343–51.

[69] Stopes and Wheeler, "Spontaneous Combustion of Coal in Relation to Its Composition and Structure, III," *Fuel*, Vol. II (1923), pp. 122–32.

tive chemical inertness of the fusain did not manifest itself except at the highest temperature used. This conclusion is supported by data on the absorption of iodine from a solution in 0.1 N KI obtained by the same investigators on the same coal.[70] This reagent is much more chemically reactive than molecular oxygen, and it was found that the bright coal absorbed 22.8 per cent by weight in 24 hours, while the dull absorbed 17.8 per cent and the fusain only 4.3 per cent. When a still more reactive reagent, iodine in Wijs solution, is used, the relative differences in chemical reactivity between the bright and the dull coal were less, and between them and fusain they were greater.[71] Similar results have been obtained with bromine solution in carbon tetrachloride.[72]

Some unpublished data have indicated that lower-rank coals may be more extensively hydrolyzed by aqueous alkali at elevated temperatures than higher-rank coals. This reaction has not been used extensively. For two Upper Silesian coals, however, the bright components were more extensively hydrolyzed (owing, in this case, possibly to oxidation) by aqueous sodium hydroxide at 350° C. than were the dull components, though the magnitude of the difference was irregularly dependent on the alkali concentration.[73] This was attributed to there being less material of humic origin and greater spore contents in the dull coals. Treatment of the bright and dull fractions of coal from the Hamstead Seam with alcoholic potash at 80° showed similar differences.[74]

SUMMARY AND CONCLUSION

An examination of published data on comparative chemical characteristics of associated petrographic components, primarily the bright and dull fractions and fusains, has been made. The separation of these components was generally made by visual inspection and criteria of petrographic purity were only infrequently given, al-

[70] Stopes and Wheeler, "Spontaneous Combustion of Coal in Relation to Its Composition and Structure, II," *op. cit.*

[71] *Ibid.*

[72] Keppeler and Borchers, *op. cit.*

[73] Keppeler and Borchers, *op. cit.*

[74] Stopes and Wheeler, "Spontaneous Combustion of Coal in Relation to Its Composition and Structure, II," *op. cit.*

though certain of the investigations have shown that the components so selected may vary in chemical composition over a considerable range. This fact may, in part, be responsible for the frequent overlapping in chemical properties and for the general impossibility of drawing conclusions to which exception cannot be cited. In this connection the work of Seyler is particularly suggestive, although additional work is necessary to justify the fundamental assumptions made in his correlation of chemical properties and petrographic composition.

In general, however, the bright coals, on a dry, ash-free basis, have lower carbon contents and calorific values and higher hydrogen, nitrogen, sulphur, and oxygen contents than the associated dull coals. The differences are even greater, and in the same direction, between the bright coals and associated fusains. Similar differences between bright coals would usually be associated with increase in rank or maturity. In the majority of cases the ash content decreases from fusain to dull coal to bright coal for the components of a given seam. While the volatile matter content of fusains is definitely lower than that of associated bright coals, the differences between the bright and dull components are indefinite.

Extensive studies have been made to find fundamental differences in chemical structure of the associated petrographic constituents without success. There appears to be a gradation of properties from one component to the next, but there is no indication of the presence of essentially distinct types of chemical compounds peculiar to any of the ingredients of banded coals. In general, the chemical reactivity decreases from the bright component to the dull to fusain; this is in accord with the general differences in chemical analysis, since chemical reactivity also usually decreases with increase in rank of coal.

To return to our original thesis, differences in *appearance* of the bands in any given coal are not adequate criteria for differences in chemical composition. Although these differences in appearance *may* be associated with differences in chemical composition, both the amount and the direction of the differences must be determined by chemical means in each case.

MODERN CONCEPTIONS OF THE PHYSICAL CONSTITUTION OF COAL AND RELATED RESEARCH IN GREAT BRITAIN[1]

C. E. MARSHALL
University of Birmingham, England

ABSTRACT

It is generally agreed that no essential differences exist between the normal coal types and constituents of American and British Carboniferous coals.

The brilliant bands of vitrain (anthraxylon) have been derived from fragments of cellular tissue, particularly the tissue of *Bothrodendron*, *Lepidodendron*, and *Sigillaria*, and also of wood tissues of gymnosperms and cycadophytes. Isolation of the various coal constituents and their examination petrologically and chemically is vital to investigations of rank and type variation.

The importance of petrographic analysis to the economic and efficient utilization of coal is becoming increasingly apparent, as is also the petrographic examination of the mineral matter in coal seams in solving problems of preparation and treatment.

INTRODUCTION

The application of the microscope to the investigation of the constitution of coal is first recorded in the work of H. T. M. Witham[2] and W. Hutton.[3] Although limited by the powers of the optical equipment then available, the work of these two pioneers served to demonstrate beyond question the vegetable origin of bituminous coals; their success was largely due to the high quality of thin sections produced at this early date.[4]

In the period which has elapsed since the publication of these early studies, numerous investigators have attacked the many problems connected with the nature and preservation of plant tissues in the solid fuels, but at no time has greater activity and interest been displayed in the micropetrology of coal than during the last thirty years. The modern phase of research upon the physical constitu-

[1] Address delivered at the Fiftieth Anniversary Celebration of the University of Chicago, September, 1941.

[2] *The Internal Structure of Fossil Vegetables* (Edinburgh, 1833).

[3] "Observations on Coals" (paper read before the Geological Society of London). Abstract published in *Proc. Geol. Soc. London*, Vol. I, p. 415.

[4] H.G.A. Hickling, "William Hutton's 'Observations on Coals,' 1833," *Trans. Inst. Min. Eng.*, Vol. XC (1936), pp. 243–53.

tion of coal can be said to have begun with the work of R. Thiessen,[5] E. C. Jeffrey,[6] H. G. A. Hickling,[7] and M. C. Stopes.[8] Their valuable contributions to our knowledge of the subject served as an effective stimulus to further research.

As would be expected, the work of coal petrologists of each of the two English-speaking nations has had a profound effect upon that of the other; unfortunately, this did not serve to prevent initial misunderstandings. Based upon the rather conflicting observations and deductions of Stopes[9] and Thiessen,[10] there were formed the so-called English and American "schools" of coal petrology, neither being fully representative of opinion in either country. Developments and modifications within both schools have led to their gradual and almost complete reconciliation in most matters of observation and interpretation; it is now generally realized that there are no essential differences in physical constitution between American and British coals of Carboniferous age.

THE COAL TYPES AND CONSTITUENTS

At a very early date it was recognized that normal seams of Carboniferous age commonly display two kinds of coal, which are distinctly contrasted as regards their physical properties. The greater part of most seams consists of bright, well-laminated coal, to which the old miners gave the name "brights"; the lamination of this coal is usually emphasized by the presence of numerous discrete layers of brilliantly black coal, commonly less than one-half inch in thickness, which are not themselves intrinsically stratified. "Dull coal" or "dulls"—gray or black earthy-looking coal in which lamination is either indistinguishable to the unaided eye or else marked by occasional fine bands of brilliantly black coal—enters into the composi-

[5] R. Thiessen and D. White, "The Origin of Coal," *Bull. U.S. Bur. Mines*, Vol. XXXVIII (1913), pp. 187–390. Thiessen, "Structure in Palaeozoic Bituminous Coals," *Bull. U.S. Bur. Mines*, Vol. CXVII (1920), pp. 1–296.

[6] "The Mode of Origin of Coal," *Jour. Geol.*, Vol. XXIII (1915).

[7] "A Contribution to the Micropetrology of Coal," *Trans. Inst. Min. Eng.*, Vol. LIII (1917), pp. 137–58.

[8] "On the Four Visible Ingredients in Banded Bituminous Coal," *Proc. Roy. Soc. Britain*, B, Vol. XC (1919), pp. 470–87.

[9] *Op. cit.* [10] *Op. cit.*

tion of many seams; occasionally it may be dominant. Bedding planes within the seam may be marked by fragments of "mineral charcoal."

In her original classification of the normal Carboniferous coals Stopes[11] recognized four ingredients or constituents, which she named "vitrain," "clarain," "durain," and "fusain"; definition and identification were based upon the properties of the hand specimen, supplemented by observations as to their appearance under the microscope. This terminology rapidly passed into general use, although considerable controversy was aroused by Stopes's observations upon the nature and origin of the constituent vitrain. In a later paper[12] the original scheme was amended and extended so as to conform as nearly as possible with petrological practice. Appropriate details will be discussed as they arise, but it may be stated here that in the new scheme the four lithological or rock types—vitrain, clarain, durain, and fusain—were retained, while a new series of names were proposed to indicate the individual constituents or "macerals." The latter were intended to be the counterparts of the petrologist's minerals, and their new names were all to be characterized by the termination "-inite."

With certain minor modifications this terminology was accepted by the Heerlen Committee.

BRIGHT COAL

Vitrain was the name given by Stopes to the discrete brilliant lamellas of ordinary bright coal. The description of the hand specimen was supplemented by observations upon the appearance of the material in thin section, where it was said to appear "uniform in its structureless nature." This statement upon the structureless character of vitrain was in direct conflict with the observations of other British coal petrologists (e.g., Hickling);[13] neither did it agree with the work and conclusions of the late Dr. Reinhardt Thiessen concerning the brilliant lamellas (anthraxylon) of American coals. The vitrain controversy continued for many years, but accumulat-

[11] *Op. cit.*

[12] Stopes, "On the Petrology of Banded Bituminous Coal," *Fuel*, Vol. XIV (1935), pp. 4–13.

[13] *Op. cit.*

ing evidence made it increasingly apparent that the brilliant lamellas were almost invariably characterized by cell structure; not infrequently the preservation retained the most minute and delicate details of the original tissue.

The amended scheme of classification proposed by Stopes in 1935 provided for vitrains with structure. In the same scheme a new term "vitrinite" was proposed as the micropetrological counterpart of vitrain, that is, to include all vitrain lenticles which were not of "rock" proportions and which were consequently to be regarded as "macerals." For reasons to be discussed later, the term "vitrinite" is considered preferable to "vitrain" for all the brilliant lamellas—whether macroscopic or microscopic—and will be used throughout the paper.

Vitrinite is sometimes preserved as isolated sheets or fragments in the roof shales associated with many coal seams and may then retain, or imprint upon the shale, some characteristic feature or ornament which permits identification of the tissue from which it has been formed. Hickling and Marshall[14] were fortunate in securing many such specimens in which details of the internal cellular structure were very well preserved. By comparison with the microstructures and preservations of these identifiable specimens, it has been possible to determine the nature and origin of a considerable proportion of the vitrinite lamellas present in most coal seams.

This investigation has been extended to the anthraxylon of American coals, and in them have been found tissues, structures, and preservations identical with those of British vitrinites.[15] It can be concluded that the origin of the material and the conditions of preservation must have been very similar.

Not all the tissues preserved in coal have been identified, but there appear to be five important sources of the vitrinite and anthraxylon of British and American Carboniferous coals: bark tissues of (1)

[14] "The Microstructure of the Coal in Certain Fossil Trees," *Trans. Inst. Min. Eng.*, Vol. LXXXIV (1932), pp. 13–23; "The Microstructure of the Coal in Certain Fossil Tree Barks," *ibid.*, Vol. LXXXVI (1933), pp. 56–75.

[15] Marshall, "Contribution to the Comparative Petrology of British and American Coals of Carboniferous Age: Anthraxylon and Vitrinite (Vitrain)," *Fuel*, Vol. XX (1941), pp. 52–59, 82–91.

Bothrodendron, (2) *Lepidodendron*, and (3) *Sigillaria;* and wood tissues of (4) gymnosperms and (5) cycadophytes.

Bothrodendroid vitrinite and anthraxylon.—The very characteristic structure of vitrinite and anthraxylon derived from the cortex of *Bothrodendron* is conspicuous and common in many seams. As seen in transverse section, there is usually developed at one face of the vitrinite (anthraxylon) sheet a narrow zone of tissue in which the cells are quite uncrushed. The radial middle lamellas are distinct, while the comparatively thin cell walls, rather darker in color, are clearly demarcated from the pale coal substance which occupies the cell cavity. In many of the cells this pale material in the cell cavity is constricted tangentially to an hourglass form, and the area between it and the cell walls is occupied by darker coal material; the latter most probably represents organic colloids absorbed from the coal peat, together with material possibly produced by the partial disintegration of the inner cell wall. The constricted hourglass structure almost certainly represents the incompletely collapsed cell sac, from which a portion of the original cell contents has been abstracted, possibly by some process comparable with plasmolysis.

The original cell sacs were connected in a radial direction by numerous and minute protoplasmic strands which traversed the tangential walls of the cells. These minute connecting processes can still be detected in many preservations, which accounts for the persistent radial orientation of the shrunken cell sacs.

Succeeding this narrow zone of uncollapsed and partly "plasmolyzed" tissue, there is usually a broad area of what appear to be rather thicker-walled cells. In each cell the cell sac is reduced to a fine, radially disposed septum, expanded at either end, where it is in contact with the tangential cell walls. This tissue has usually suffered some compression.

As the second face of the vitrinite layer is approached, the evidence of radial compression becomes more pronounced. The prominent radial middle lamellas are contorted, and the cell cavities greatly reduced; in many specimens the lumens are completely closed, and the preservation represents little more than a compacted mass of cell-wall material. Even at this advanced stage of

compression, the greatly distorted and folded, radial middle lamellas are still very prominent.

In many specimens this zone of highly compacted cell-wall material preserved as vitrinite may persist to, and form the second face of, the sheet. In other examples it is succeeded by an outer layer of tissue in which the condition of preservation changes quite rapidly from that of vitrinite to fusinite (fusain), which then forms the second face of the specimen. The change from vitrinite to fusinite is quite progressive and passes through all intermediate conditions; it is marked by the disappearance of the cell contents, the increasing opacity of the cell walls, and their marked tendency to yield to compression by fracture. The conditions intermediate between vitrinite and fusinite were originally termed "vitri-fusain"[16] but would now be better rendered as "vitri-fusinite."

In longitudinal sections the cells of bothrodendroid tissues appear long and fiber-like.

Lepidodendroid vitrinite and anthraxylon.—The structure and preservation of identified cortical tissues of the Lepidodendreae are very similar to those of the Bothrodendreae, from which it is practically impossible to distinguish them in the majority of vitrinite sections. Some preservations, however, as compared with those of *Bothrodendron*, may show one or more of three possible differences in structure: (1) the contents of the original cell sacs of the thinner-walled tissues appear to be extraordinarily rich in minute gas cavities and opaque bodies; (2) the outermost tissue consists of thick-walled cells quite unaffected by compression; (3) the cuticular covering of the leaf cushions may be preserved. The greater part of the tissues are usually of the thinner-walled plasmolyzed type.

A tissue probably derived from the bark of *Lepidophlois wunchianus*[17] is characterized by a peculiar median thickening of the cell wall. It is not uncommonly preserved as vitrinite and anthraxylon in Carboniferous coals.

Sigillarian vitrinite and anthraxylon.—The structure of the ma-

[16] Hickling and Marshall, "The Microstructure of the Coal in Certain Fossil Tree Barks," *op. cit.*

[17] J. Walton, "Scottish Lower Carboniferous Plants: The Fossil Hollow Trees of Arran and Their Branches," *Trans. Roy. Soc. Edin.*, Vol. LVIII (1935).

jority of sigillarian cortexes preserved in British and American coals is characteristic. As seen in section, they take the form of (1) alternate radial files of thick-walled and thin-walled cells, (2) "islands" or groups of thin-walled cells in a "ground tissue" of thick-walled cells, or (3) islands or groups of thick-walled cells in a ground tissue of thin-walled cells.

All three relations may be observed in a single vitrinite section and traced through intermediate conditions from one to another. The original cortex was apparently constituted of two mutually interpenetrating, three-dimensional lattices, one of parenchyma (thin-walled cells) and the other of sclerenchyma (thick-walled cells). Their relationship, as seen in thin section, depends upon the position and orientation of the plane of the section relative to the interpenetrating lattices; if the tissues have been at all crumpled or distorted, considerable variation will be apparent even in a single section.

The thick-walled cells tend to be subangular to rectangular, with the cell cavities represented by small irregular or barlike features; the radial middle lamellas are usually distinct. The thin-walled cells may be preserved in an almost completely undistorted condition, with their cell cavities occupied by golden-yellow coal substance; more commonly they have been compressed and distorted.

Different species of *Sigillaria* preserved as vitrinite tend to exhibit slight differences and modifications of the common characteristic structure. Strands of very thick-walled cells may appear at one face of the specimen and "finger-out" toward the second and presumably outer face. The inner side of the cortex may retain small groups of very thick-walled, rectangular cells in a vitrifusinite "matrix" of smashed cell-wall material. The outer cortical face may be formed of rectangular thick-walled cells arranged with their longer axes parallel to the surface of the sheet; beneath this outermost layer a zone of greatly distorted thinner-walled cells may be developed. The cortexes of certain of the Sigillariae of Rhytidolepis type may be constituted entirely of greatly compacted and elongated cells with their cavities completely closed.

A number of these structural variations have been identified as belonging to different sigillarian species.

Vitrinite derived from gymnospermous wood.—Transverse sections

of vitrinite and anthraxylon derived from gymnospermous wood reveal that the tissue is almost invariably greatly compressed. The positions of the cell cavities are marked by discontinuous, pale, sinuous lines in the darker mass of the compacted cell walls; the pale material apparently represents the inner layer of the cell wall. Uncollapsed cells are occupied by resin-like material usually containing numerous minute gas cavities and inclusions; the medullary rays are commonly greatly distorted but relatively uncompressed. The middle lamellas are discernible with difficulty, but short, pale bars representing the cavities of the characteristic crossed-bordered pits are quite conspicuous.

In vertical sections the cavities of the wood fibers are marked by long pale lines, while the medullary rays are most prominent as "strings" of oval to subrectangular cells filled by resin-like material. The pits appear almost invariably as "chains" of pale, short, barlike features.

Owing to the severe compression and folding of the tissues, the orientation of longitudinal sections relative to any particular botanical direction varies continuously and considerably but tends to be dominantly tangential. Consequently, the characteristic crossed-bordered nature of the pits which can be observed in radial sections is only revealed in restricted and comparatively infrequent portions of the section.

Vitrinite derived from cycadophytes.—Certain tissues preserved as vitrinite and anthraxylon have not yet been positively identified but retain certain characters which appear to be typical of the cycadophytes.[18] Tissues of small, thick-walled cells alternate with zones in which the structure is practically indiscernible. There is usually a concentration of large resin-like bodies toward one face of the vitrinite sheet. In favorable sections rows of elongated, oval-bordered pits may be revealed.

The structures and preservations which have been so briefly described include those most commonly found in the brilliant discrete layers of British and American coals. Vitrinites formed from these tissues constitute a considerable part of many coal seams. Bark tissues of the lycopods predominate, but the proportion of the wood

[18] R. Thiessen and G. C. Sprunk, "Microscopic and Petrographic Studies of Certain American Coals," *U.S. Bur. Mines Tech. Paper 564* (1934), pp. 1–71.

tissues tends to be underestimated as a result of their less conspicuous preservation.

Other structures and tissues are preserved in vitrinite (anthraxylon), more especially in the smaller frgaments; some have been identified as representing leaf tissues and sporangial material, while others remain as yet unidentified. Many of the smaller vitrinite laminas represent more highly disintegrated wood and bark tissues.

Regarding the mode of preservation of vitrinite and anthraxylon, it is interesting to note that they have usually yielded to compression by "plastic" deformation; evidence of fracturing is not commonly found in true vitrinite. Although by no means invariably so, the tissues which have generally best resisted compression are either thin-walled or consist of very thick-walled cells. In the latter case, the cell cavities were already minute, and pressure could effect but little further compaction in the tissue; the well-preserved thin-walled cells are filled either by resin-like material or by coal substance, of which a considerable proportion must have been absorbed from the coal peat. Tissues with cells of medium-wall thickness appear to have been less permeable, less amenable to impregnation, and consequently more subject to collapse.

Fusain is the name given by Stopes[19] to preservations of cellular tissue in which the cell walls remain opaque even in the thinnest sections. The term "fusinite" was proposed by Stopes[20] as an alternative to "fusain" in the micropetrological terminology.

The tissue may be preserved without serious disorganization, or the cell walls may be fractured and compacted. The cell cavities usually either are empty or are filled by mineral matter; apparently they are never occupied by coal substance—a fact which may be significant in any consideration of the process of "fusainization." Both wood and bark tissues may be preserved with opaque cell walls.

As already mentioned, all conditions of preservation between fusinite and vitrinite may be found in different cellular tissues, or even within a single plant fragment.

Clarain.—The moderately bright, finely laminated coal which constitutes a considerable part of many seams was named "clarain" by

[19] "On the Four . . . . ," *op. cit.* [20] "On the Petrology . . . . ," *op. cit.*

Stopes;[21] it corresponds to the anthraxylous and translucent attritus of American coals. The fine lamination of clarain is due to the layering and compression of smaller plant fragments and debris in various stages of disintegration, including "recognizable intercalated zones of vitrinite."[22] Much of the debris is preserved in the condition of vitrinite and represents smaller fragments of wood and bark, leaf tissues, and similar material. Fusain (fusinite), resin-like bodies, cuticles, megaspores, and microspores are not uncommon and may tend to be concentrated locally within the clarain. A smaller proportion of the finer debris tends to be more opaque than the bulk of the material and almost certainly represents highly disintegrated plant fragments preserved in the condition of vitri-fusinite (semi-fusinite) and fusinite.

For this finely divided, more opaque material, Stopes suggested the term "micronite," which the Heerlen Committee adjusted to "micrinite." C. A. Seyler[23] refers to the darker, but not quite opaque, debris as "intermediates."

DULL COAL

Durain.—Lamination is not conspicuous in the dull, gray or black coal of British seams and may only be apparent where emphasized by the presence of typical shredlike strands of vitrinite.

Microscopically the dull coals are characterized by their high content of fusinite, micrinite, and semiopaque "intermediates." Megaspores and microspores are very common and may be sufficiently concentrated to form a considerable part of the coal; this is notably the case in the black durains. Low content of spore material is usually associated with the gray durains. Thin strands and shreds of vitrinite, cuticles, and resin bodies are all quite common in the dull coals.

In all essential details of physical constitution the durains correspond with the splint coals of America.

Cannel and boghead coals.—Typical cannel coals are characterized by the highly disintegrated condition of the vegetable debris, of which a high proportion is translucent in thin section. Fragments of

[21] "On the Four . . . . ," *op. cit.* [22] "On the Petrology . . . . ," *op. cit.*

[23] "Petrology and the Classification of Coal," *Proc. So. Wales Inst. of Eng.*, Vol. LIII (1938), p. 4.

cuticles, spore exines, and resin bodies, together with a considerable amount of finely divided material which is apparently preserved in the condition of vitrinite, constitute the greater part of the normal cannel coals.

Such typical cannel coals are distinguished from clarain by the more highly comminuted nature of the plant ingredients; transition types are quite common. Increased proportions of micrinite and fusinite in the normal cannels mark an approach toward typical durains and splint coals.

A third direction of variation in the cannel coals is toward the algal cannels, bogheads, and torbanites. The recent work of B. N. Temperley[24] has demonstrated that the "yellow bodies" characteristic of these coals are colonies of an alga very closely resembling the living alga, *Botryococcus brauni*. The appearance of these bodies in an otherwise typical cannel marks the transition to the algal cannels, and their further concentration leads to the bogheads and torbanites.

PETROLOGICAL CLASSIFICATION OF THE COAL TYPES AND CONSTITUENTS

The original classification of the banded bituminous coals proposed by Stopes[25] was based upon the lithological characters of the "ingredients," supplemented by certain observations upon their appearance under the microscope. In a later paper[26] adjustments were made in the original scheme, which was revised and extended to conform with micropetrological data and petrological practice. Apart from certain slight alterations, this scheme was accepted by the Heerlen Committee.[27] An abbreviated form of Stopes's latest classification and the Heerlen amendments are given in Tables 1 and 2.

Although in many respects a considerable improvement upon the original scheme, this latest classification might be improved by certain comparatively minor readjustments; they would have the further merit of bringing the British scheme more completely into agreement with the American type of classification.

In her latest paper Stopes proposes the term "maceral" to cor-

[24] "Botryococcus and the Algal Coals—Part II," *Trans. Roy. Soc. Edin.*, Vol. LVIII (1936), pp. 855–68.

[25] "On the Four . . . . ," *op. cit.* [26] Stopes, "On the Petrology . . . . ," *op. cit.*

[27] W. J. Jongmans, R. G. Koopmans, G. Roos, and C. A. Seyler, "Nomenclature of Coal Petrography," *Fuel*, Vol. XV (1936), pp. 14–15.

TABLE 1

ABBREVIATED FORM OF STOPES'S "CLASSIFICATION OF THE COAL INGREDIENTS," 1935

LITHOLOGICAL CLASSIFICATION				MICROPETROLOGICAL			
Appearance of Hand Specimens	Lithological Name			Appearance of Microsection	Macerals		
Thin horizontal bands visible to the naked eye; up to 20 mm. thick. Not intrinsically stratified but may show striations due to plant structure	*Vitrain*	*Eu-vitrain* (structureless	*Ulmain:* completely jellified plant material	Uniform when uniformly thin	*Ulminite*	*Eu-vitrinite*	*Vitrinite*
			Collain: redeposited ulmin compounds precipitated from solution	Uniform when uniformly thin	*Collinite*		
		Pro-vitrain (structured)	*Periblain:* where its origin is evidently bark	Translucent golden gel; structure shadowy, ghostlike or faint, sometimes distinct	*Periblinite*	*Pro-vitrinite*	
			Suberain: where its corky origin is evident	Translucent golden gel with corky structure	*Suberinite*		
			Xylain: where its woody origin is evident	Translucent golden gel; xylem structure shadowy, ghostlike or faint, sometimes distinct	*Xylinite*		
Irregular wedges lying on bedding planes at various angles. Resembles charcoal in appearance	*Fusain*			"Carbonized" cell structures with opaque walls	*Fusinite*		*Fusinite*
Thin to very thick bands, intrinsically stratified	*Clarain*			Striated appearance due to fragments of plant tissues in various stages of disintegration	*Xylinite* *Periblinite* *Suberinite* *Collinite* *Resinite*	Distinctive	*Clarinite*
				Intercalated zones of vitrinite. Cuticles, spores, resin bodies Fusain not infrequent	*Ulminite* *Cutinite* *Exinite* *Fusinite* *Micronite*	Less distinctive	
Solid bands with a close firm texture. Stratification generally absent	*Durain*			Fine granular groundmass, often semiopaque even in very thin sections. Spore exines are generally conspicuous. Resin bodies and larger cuticles may be locally dominant	*Micronite* *Exinite* *Cutinite* *Resinite*	Distinctive	*Durinite*
					Collinite *Xylinite* *Suberinite* *Ulminite* *Fusinite*	Less distinctive	

respond with the petrologists' "mineral"; typical macerals are vitrinite, resinite, cutinite, and sporinite. A slight, but unavoidable, confusion may arise, for example, in the case of a fragment of resinous wood, which preserved as vitrinite (maceral), contains resinite (another maceral). This need not be considered as breaking down the parallel with petrological practice, for many minerals frequently contain other mineral inclusions. As was apparently originally intended, a

TABLE 2

HEERLEN COMMITTEE AMENDMENTS

Rock Types (Termination "-ain")	Macerals (Termination "-inite")		Notes
Vitrain	Vitrinite	Collinite	May be subdivided if desired
		Telinite	May be subdivided according to botanical origin if desired (xylinite, suberinite, periblinite)—usually considered unnecessary
	Semifusinite		Intermediate between vitrinite and fusinite
Fusain	Fusinite		Opaque cellular tissue
	Micrinite		Opaque "residuum"
	Exinite	Sporinite	Spore material
		Cutinite	Cuticle material
Clarain	.....		Dominantly vitrinite with some exinite and other macerals
Durain	.....		Dominantly micrinite with exinite

maceral may be considered as an "organic unit," that is, as a single fragment or portion of plant debris.

In the new scheme of Stopes, both "vitrain" (coal "rock") and "vitrinite" (maceral) are used to designate the brilliant lamellas. The distinction drawn between the two is based upon the power of the unaided eye to distinguish vitrain ("rock") in the block of coal, while the vitrinite (maceral) is "only visible when thin sections are prepared for the microscope."[28] In this way a very arbitrary and ill-defined line is drawn between two essentially similar materials. Whether it is microscopic or macroscopic, each of the laminas of

[28] "On the Petrology . . . ," *op. cit.*

brilliant black coal in bituminous seams represents a *single* fragment of cellular tissue. It is not an aggregate of plant fragments and should, therefore, be regarded as a single maceral and not as a "rock" or coal type. This is quite in keeping with general petrological practice; individual optical units or mineral grains are regarded as minerals whatever their dimensions, and consolidated aggregates of mineral particles constitute a rock.

It would thus appear that all bright lamellas should be regarded as constituents or macerals and termed "vitrinite." If "vitrain" is to be retained as a lithological or rock name, it can be logically applied only to an aggregate of individuals of the maceral vitrinite. In this case vitrain would obviously overlap clarain, which is a true coal rock, with vitrinite as the dominant constituent. The term "vitrain" thus appears superfluous and might be abandoned in favor of "vitrinite."

"Fusain" and "fusinite" stand in a similar relationship to "vitrain" and "vitrinite," and similar arguments can be developed regarding the use of these terms. There are grounds, however, for the retention of the term "fusain" to designate the fusinite-rich layers which occur quite frequently in many seams, although their proportions do not approach those of the two main coal rocks—clarain and durain—and it is doubtful if they should be given equal prominence in any scheme of classification.

Returning now to the question of classification, it has been suggested that "vitrain" should be regarded not as a type of coal but as a maceral, a common constituent of bright coal. If this view is accepted, then it is logical to extend the use of the term "clarain" to include *all* the bright coal. Clarain would thus become the coal *type*, exactly comparable with the American bright-coal type and characterized by the dominant maceral vitrinite (vitrain) in either macroscopic or microscopic laminas. Durain would remain as the dull-coal type, corresponding to the American splint coal.

Further discussion of petrological classification must be postponed, but a suggested revision of the British terminology of coal petrology is indicated in Table 3. The main coal types, including the cannels, are four in number (two in the normal coals) and can be

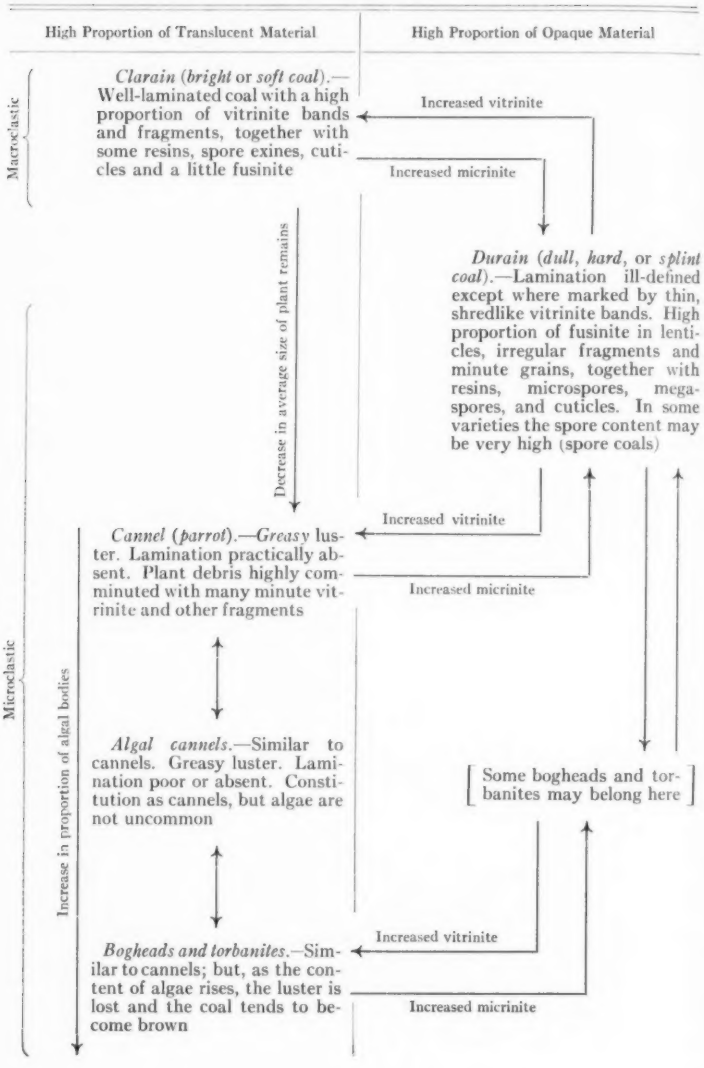
TABLE 3

SUGGESTED AMENDED FORM OF PETROLOGICAL CLASSIFICATION

Coal Types (Cf. Rock Types)	Macerals (Cf. Minerals)	
I. Macroclastic A. Clarain..	1. *Vitrinite*—dominant maceral (essential); may be subdivided into— *a*) *Pro-vitrinite* or *tellinite* (structured) (i) Xylinite—from wood tissues (ii) Suberinite—from corky tissues (iii) Periblinite—from cortical tissues *b*) *Eu-vitrinite* or *collinite* (structureless) (iv) Ulminite—portions of (i), (ii), and (iii) in which structure is obliterated (v) Collinite—from colloidal solutions	
	2. *Fusinite*—highly "carbonized" cellular tissue—may be from wood, bark or cork tissues	Accessory macerals
	3. *Cutinite*—from cuticles	
	4. *Sporinite*—from spore exines, both macrospores and microspores	
	5. *Micrinite*—from finely divided "carbonized" tissues and debris	
II. Microclastic B. Durain..	1. *Vitrinite*—usually in shredlike strands or thin layers A, 1, *a* (i), (ii), (iii), or *b* (iv)	Micrinite may be considered the most characteristic or essential maceral; concentration of other macerals may occur locally
	2. *Fusinite*—commonly in greater proportion than in A	
	3. *Cutinite*—quite common; may be concentrated locally	
	4. *Sporinite*—very common in some durains; may be concentrated locally	
	5. *Micrinite*—usually forms the matrix of the durain	
C. Cannel..	1. *Vitrinite*—very high comminuted and disintegrated, with the exception of occasional shredlike strands	Dominantly a very finely disintegrated translucent attritus or debris
	2. *Fusinite*—identifiable fragments rare	
	3. *Cutinite*—usually finely fragmented	
	4. *Sporinite*—microspores commonly whole, but megaspores usually broken up	
	5. *Micrinite*—low concentration in more typical cannels; higher concentration marks transition toward durain	
D. Boghead	1. *Vitrinite*—very highly disintegrated, with the exception of occasional shredlike strands	Proportion of translucent attritus or debris tends to be reduced
	2. *Fusinite*—identifiable fragments rare	
	3. *Cutinite*—usually finely fragmented	
	4. *Sporinite*—microspores commonly whole; megaspores usually broken	
	5. *Micrinite*—may attain not inconsiderable proportions	
	6. *Algae*—tend to become the dominant constituent	

TABLE 4

TYPE RELATIONS AND CLASSIFICATION OF COALS


High Proportion of Translucent Material
High Proportion of Opaque Material
Macroclastic
Microclastic
Clarain (bright or soft coal).—Well-laminated coal with a high proportion of vitrinite bands and fragments, together with some resins, spore exines, cuticles and a little fusinite
Increased vitrinite
Increased micrinite
Durain (dull, hard, or splint coal).—Lamination ill-defined except where marked by thin, shredlike vitrinite bands. High proportion of fusinite in lenticles, irregular fragments and minute grains, together with resins, microspores, megaspores, and cuticles. In some varieties the spore content may be very high (spore coals)
Decrease in average size of plant remains
Increased vitrinite
Cannel (parrot).—Greasy luster. Lamination practically absent. Plant debris highly comminuted with many minute vitrinite and other fragments
Increased micrinite
Increase in proportion of algal bodies
Algal cannels.—Similar to cannels. Greasy luster. Lamination poor or absent. Constitution as cannels, but algae are not uncommon
Some bogheads and torbanites may belong here
Increased vitrinite
Bogheads and torbanites.—Similar to cannels; but, as the content of algae rises, the luster is lost and the coal tends to become brown
Increased micrinite

broadly subdivided according to grain size.[29] The relations of the coal types are roughly indicated in Table 4; transitions or subtypes can be recognized and may be named according to their relations with the main types. For example, a cannel with an increased proportion of opaque and semiopaque debris (i.e., intermediate to cannel and durain) might be termed "micrinite cannel," just as cannel with a slight concentration of algae is termed an "algal cannel."

Whatever petrological terminology is finally accepted for academic and industrial use, it is to be hoped that it may be as simple as possible. Unnecessary elaboration, duplication, and multiplicity of terms produce confusion; a scheme of classification should be adequate for the real needs of the specialist and acceptable to the industrial engineer.

RANK AND THE PHYSICAL CONSTITUTION OF COAL

While the nature of rank variation can be readily stated in general terms, it is much more difficult to define specifically. Early efforts to establish a chemical basis for rank measurement were affected by complications due to variation in coal type.

A considerable attention has been given in recent years to the chemical nature and composition of the coal types and constituents (macerals). Much of this work has been primarily concerned with problems of utilization, but it is also of considerable importance to the various problems of rank variation and classification for industrial purposes.

As vitrinite forms such a large part of many seams, it is comparatively easily extracted without contamination and is probably the purest coal obtainable; it offers a particularly suitable field for research upon the petrological and chemical variations of the solid fuels.

Many samples of vitrinite from seams of all ages and ranks have been examined chemically and microscopically with interesting results. Groups of vitrinite specimens from restricted areas in Carboniferous seams have been investigated with a view to establishing any possible connection between chemical composition and either the kind of tissue from which the vitrinite was formed or its state

[29] Hickling, "The Properties of Coal as Determined by Their Mode of Origin," *Jour. Inst. Fuel*, Vol. V (1932).

of preservation. Apart from a tendency toward increased difficulty of microscopic resolution of structural details, no significant relationship could be found to exist between chemical and physical constitution. The range of chemical composition within each group was not large, amounting to between 1.0 and 1.5 per cent for carbon and oxygen and not more than 0.4 per cent for hydrogen.

Similarly, vitrinite samples from a restricted area in a lignite seam showed no significant relationship between chemical composition and the nature or preservation of the plant tissues from which they had been formed. The range of chemical variation within the group was greater than in the bituminous coals, amounting to approximately 3 per cent in carbon and oxygen and 0.7 per cent in hydrogen.

Other groups of vitrinites have been examined with similar results. There does not appear to be any significant relationship between the petrological and chemical characters of vitrinite specimens.

When the carbon, oxygen, and hydrogen contents for vitrinites from coals of all ages and ranks are graphed, there is obtained a curve similar to the "coal belt" of Hickling.[30] It is much more restricted in width, however, corresponding to a smaller range of variation in the content of hydrogen. The linear nature of the carbon-oxygen relationship is very striking.

It has been suggested that the rank of a seam may be determined by that of its vitrinite, measured either on a chemical basis or by the variation in some physical property. The range of composition, which may be exhibited between vitrinite specimens taken from even the same pillar sample, indicates that consistent measurement of rank on the basis of the chemical composition of vitrinite is not assured. Possibly the mean of many analyses of vitrinite samples taken from the seam in a restricted area may give more satisfactory data for rank measurement.

However, the variation in chemical composition of specimens of the constituent vitrinite from a single pillar section and the diversity of chemical character and behavior exhibited by different constituents in a single coal sample make it evident that rank classification for either academic or industrial purposes must take into consideration both the petrographic and the chemical properties of the coal.

[30] *Ibid.*

PETROGRAPHIC ANALYSIS

Despite the long history of the application of the microscope to the academic investigation of coal problems, it is only in very recent years that the economic value of petrographic analysis has been appreciated. Modern work has emphasized the importance of careful selection of the best type of coal for many industrial purposes, such as hydrogenation and the production of high-quality metallurgical coke.

The chemical composition, characters, and properties of a solid fuel have been decided by certain factors which are largely interdependent. The nature, form, and chemical composition of the original plant debris, its resistance to decay under the conditions prevailing in the coal peat and the segregation of certain kinds of materials or preservations gave rise to the various coal types. The metamorphic effects of geological processes brought about various changes in the physical and chemical properties of the coal-peat types and gave rise to rank variation. Recent work has tended to show that in the peats and very immature brown coals chemical changes very similar to those associated with rank variation may have already begun to operate to a not inconsiderable extent. In these low-rank fuels it may consequently be difficult to differentiate between type and rank variation on chemical grounds alone. In the higher-rank coals the chemical differences between the coal types tend to become obscured, although they can usually be differentiated microscopically.

With these facts in mind and in view of the complexity of the history of coal formation and the processes involved, it is not surprising to find that coals of similar elemental composition may be of different types, with contrasted chemical characters and physical properties; coal types which *superficially* appear to be similar may also have different chemical compositions and properties.

Consequently, in the economic utilization of the solid fuels, petrological investigation may be of major importance. Vital information may possibly be obtained which could not be gained by chemical means alone. The technique is usually rapid in application and low in cost.

In recent years increased attention has been given to the detailed quantitative and qualitative petrographic analysis of coals. The

work of Dr. C. A. Seyler[31] is particularly interesting. Polished sections are used in conjunction with an integrating stage for the planimetric estimation of the constituents, including the intermediates (i.e., the vitri-fusinites or semifusinites) and other fine debris. Seyler has given particular attention to these intermediates, using the Berek photometer to measure their reflectivity (transparency), and reports that, instead of forming a continuous series, they are limited to a few quite well-defined stages (or intermediates) between vitrinite and fusinite. It is further stated that the proportions of the various intermediates present appear to be characteristic of any coal and may form a basis for seam correlation.

It is apparent that many grave difficulties must be overcome in connection with the technique of such detailed petrographic analysis. The identification of the nature of the intermediates and other small constituents, as well as the distinction between vitrinite, fusinite, and semifusinite, depends largely upon the measurement of their reflectivity. Consequently, a perfectly uniform and standard polish, without relief effects and without smear, must be produced over the whole coal surface. Internal reflections from such structural discontinuities as the lower-bounding surface of the smaller particles, minute fractures, and lamination of the cellular tissues (packed cell walls, etc.) may all tend to introduce errors. Dr. Seyler's later work has only appeared as yet in the form of interim reports, but further information upon the success of the technique will be awaited with interest.

As the reserves of coals most suitable for specialized industrial purposes approach exhaustion, it is highly probable that blending will become of paramount importance. Where blending is now in operation, microscopic examination and control have proved to be of considerable value in its successful development.

Difficulties of seam correlation and related problems of mine development in areas of more complex geological structure have been successfully overcome by petrographic studies of the coals concerned. The method of correlation by microspores, as developed by

[31] *Op. cit.; Report of Fuel Research Board for the Year Ended March 31st, 1939* (London: H.M. Stat. Off., 1939).

Raistrick, has proved of considerable value, although it is not beyond criticism and may not be universally applicable or invariably successful. Mention has already been made of Seyler's suggestion of a new method of seam correlation on the basis of their proportions of the intermediates; a detailed account of the method and results has not yet been published.

Petrological investigation is not confined to the organic constituents of the seam but is extended to the examination of the mineral matter. Determination of the nature and distribution of the pyritic material, for example, may be of vital importance to questions of cleaning and utilization and can only be successfully accomplished when chemical analysis is supplemented by microscopic examination. Not infrequently the microscopic examination alone provides information not readily obtainable in any other way and adequate for the solution of many problems of coal cleaning. Costs of such an examination are low, and the execution is rapid.

CONCLUSION

The application of petrographic technique to the elucidation of coal problems—both academic and economic—is increasing and will undoubtedly play an important part in the economy of coal-mining and utilization.

It is now generally accepted that there are no essential differences of physical constitution between American and British Carboniferous coals. The officers of the State Geological Survey of Illinois have long recognized this fact; it is shown in their work[32] and by the adoption and use of the English terminology. The late Dr. Reinhardt Thiessen believed that there were no essential petrological differences between British and American coals.

Consequently, there is every reason to hope that future research in the two countries may continue on a fully reciprocal basis and to our mutual gain. The production of a common terminology should not be impossible and would probably assist in bringing into even closer co-operation all who are interested in the petrology of coal.

[32] G. H. Cady, "The Physical Constitution of Illinois Coal and Its Significance in Regard to Utilization," *Proc. Ill. Min. Inst.*, 1933, pp. 1–19. "Nomenclature of the Megascopic Description of Illinois Coals," *Ill. Stat Geol. Surv. Circ. 46* (1939), pp. 475–94.

PRACTICAL SIGNIFICANCE OF THE PHYSICAL CONSTITUTION OF COAL IN COAL PREPARATION[1]

LOUIS C. McCABE
Office of the Chief of Engineers, War Department

ABSTRACT

The petrographic investigations of coal of the last two decades have stimulated applied research in the field of preparation and utilization. Definition of the different types and varieties of coal was followed by the accumulation of a body of information on the specific physical characteristics.

Differences in specific gravity, conductivity, and friability have been utilized in commercial and laboratory preparation to separate coals into their component parts. The availability of quantities of the different types in concentrated form has made large-scale combustion research possible. Laboratory tests for ignition temperature, agglutinating value, and swelling index are being perfected and, when correlated with coking, briquetting, and combustion practice, will facilitate the solution of problems arising in these fields.

INTRODUCTION

The petrographic investigations of the last two decades have stimulated applied research in the field of coal preparation and utilization and have clarified a number of combustion problems which were not previously understood. The petrographic method as applied to coal preparation and utilization may now be directed toward improving, refining, and expanding the use of coal.

After the initial observation that there were differences in the appearance of coal, it followed that these differences should be submitted to measurement. The measurements employed were naturally those which had been applied and found valuable in the classification of the other economic minerals and rocks.

Among the most useful physical tests applicable to coal are those which measure friability, grindability, specific gravity, and weathering characteristics. Of equal importance are measurements which will permit the prediction of the behavior of coal when heat is applied in the presence or absence of oxygen.

[1] Address delivered at the Fiftieth Anniversary Celebration of the University of Chicago, September, 1941.

Friability is an important characteristic of coal from the time the seam is opened to production until the coal is consumed. This characteristic may be a phenomenon of rank which is reflected in the entire coal seam, as in the Pocahontas coals, or a reflection of type with many friabilities in the same seam, as in the banded coals of the eastern interior coal fields. It is the latter type with which this paper is concerned.

EFFECT OF PETROGRAPHY ON MINING AND PREPARATION

A seam high in fusain or vitrain responds more readily to cutting and shooting than does one high in clarain or durain. Not only does the petrographic nature affect the cost of mining the coal, but it may be an important factor in the safety of the mine and in the amount of salable coal that may be taken from it. The dusty coal mines in the high volatile fields are in the coal beds high in fusain. Mines in block or splint (durain) coals are not normally dusty. In general, mines working nonbanded coals—that is, splint-, cannel-, and clarain-type coals—are free from dust. Generally the cost of shooting such coal is high, but the proportion of lump is greater than in mines containing a large percentage of vitrain and fusain where preparation demands the removal of dust; as much as 5 per cent of the production may be lost in the preparation plant due to the removal of dust. Such dusts are largely fusain, for which there is no ready market. Because of differences in the friability of the constituents, coals of the banded type may frequently be screened into several increments, each differing from the other and all unlike the parent-seam. Thus it is possible for a single coal bed to produce a 100-mesh to 0-dust which is 75 per cent fusain, a $\frac{1}{8}$–100-inch-mesh product which is 80 per cent vitrain, and a 3–2-inch nut coal which is 85 per cent clarain. Another mine employing selective mining may produce a 6-inch lump coal which is almost entirely splint or durain and a 6-inch to 0 size which is of the bright banded type. These differences in friability give rise to numerous problems in the marketing and utilization of coals. The difficulties encountered in segregation of coal constitute a problem not only of size but also of the petrographic character of the size.

PROCESSING AND UTILIZATION

Fusain is noncoking and in excess of 15 or 20 per cent acts to weaken the structure of both coke and briquettes, but it has been observed that in smaller quantities the addition of it to the charge of a coke oven may be beneficial to the coke structure. The numerous minor fractures are distributed around each individual fusain particle instead of being combined to form the major fractures characteristic of highly fingered coke.

The sizing practice employed in parts of the Illinois field concentrates vitrain in the sizes used for domestic stoker fuel. In some instances, particularly in mild weather, when the stoker operates infrequently, coke is formed from the vitrain more rapidly than it is burned. Some producers have overcome this tendency by crushing the larger clarain sizes, which are free burning, and adding them to the coal produced in normal screening practice.

A more refined procedure, based on the difference in friability of the banded ingredients and affording closer control of the products than is possible in the normal course of mining and screening, was developed by Edwin Hoffman.[2] In this process, which was in the pilot-plant stage in 1932, the coal is passed through a hammer mill and then screened into fractions in which the various coal components are concentrated. This preparation made it possible to control carefully the coking process in which bright coal was used and provided lump domestic fuel from the associated dull coal (durain).

Because of the low grinding costs, coals which can be readily pulverized are usually specified for powdered-fuel plants. A recent United States Bureau of Mines publication concerned with this problem reports on the energy consumed in pulverizing the four coal constituents.[3]

FRIABILITY OF COAL CONSTITUENTS

Contrary to general belief, the ash-bearing constituents are not always most resistant to crushing, as was shown in tests of coal

[2] "Die petrographischen Kohlenbestandteile und ihre aufbereitungstechnische Trennung," *Jahr. d. preuss. geol. Landesanstalt*, Vol. LI (1930), pp. 253–89.

[3] Arno C. Fieldner and W. E. Rice, "Annual Report of Research and Technologic Work on Coal: Fiscal year 1940," *U.S. Bur. Mines Inf. Circ. 7143* (1940), pp. 23–24.

constituents from the southern Illinois field. The net power consumed in crushing the constituents from −20 mesh to −150 mesh with the ash content of each, is shown in Table 1. It is shown that the durain, the hardest constituent, contains less ash than the clarain, although comparison of the values for fusain with any of the

TABLE 1

POWER REQUIRED TO CRUSH COAL CONSTITUENTS

Coal Constituent	Fusain	Vitrain	Clarain	Durain
Net horsepower hours per ton of −150-mesh product	1.8	3.8	5.1	13.6
Ash	15.6%	2.2%	8.3%	5.2%

others is even more startling. It has been recognized that fusain is the most easily crushed constituent, in spite of its relatively large percentage of ash.

SEPARATION AND CONCENTRATION METHODS

In some instances, highly sensitive specific-gravity methods will separate one or more of the banded ingredients from a crushed aggregate. Low-ash vitrain has been separated when the coal in which it occurred was crushed to pass a 10-mesh screen and then immersed in a solution of 1.23 specific gravity. However, low-ash fusain and durain may be of lower specific gravity.

Oil flotation has been employed in the laboratory to effect excellent separations of coal into its various components; this method could be employed commercially if there were necessity of such application.

CONCLUSION

As coal petrography defines the different macerals of coal more accurately, methods for isolating them will be perfected. Small amounts of such substances as resinite and cutinite will be isolated, analyzed, and tested. In such processes as hydrogenation, preparation will exclude the spores and cuticles and high-ash portions which are not readily liquefied. Much can be done in the preparation of some coals to improve their coking characteristics. Considerable has

been accomplished in the measurement of swelling characteristics of coal, but there are still lacking satisfactory test methods and standards for evaluating many of the phenomena which refined methods of preparation will make it possible to explore.

A most regrettable lack of imagination is demonstrated by the attitude which sees the salvation of the coal industry in an expanding use of coal purely as a raw fuel. While just now the trend is in that direction, it is an ephemeral condition at best. A sound program for the coal industry will not overlook the possibility of new materials of all kinds, plastics being only one of the many possibilities. In such a scheme coal petrography applied to preparation will have an important role.

INFLUENCE OF PHYSICAL CONSTITUTION OF COAL UPON ITS CHEMICAL, HYDROGENATION, AND CARBONIZATION PROPERTIES[1]

GEORGE C. SPRUNK
Bureau of Mines, Pittsburgh, Pa.

ABSTRACT

Coal is a heterogeneous mass of several physically and chemically different classes of plant constituents that have accumulated in various proportions during the peat stage. Different blends of these constituents and the amount of biochemical changes in the peat stage result in the common types of coal known as "bright coal," "semisplint," "splint," "cannel," and "boghead."

From the data obtained in the present work it is evident that the type, as well as the rank, of coal must be considered whenever differences in chemical, hydrogenation, and coking properties are to be explained.

INTRODUCTION

One of the first methods used to investigate the physical constitution of coal was to examine the coal microscopically. Most authorities agree that the year 1833—more than one hundred years ago—marked the first of such attempts. In that year, on January 9, William Hutton, an Englishman, presented a paper before the Geological Society of London on "Observations on Coals," in which he records the first effort to study coal by means of transparent sections under the microscope.[2]

The aim of the first coal microscopists was to detect the kinds of plants and the parts of plants that contributed to the formation of the different types of coal. In this investigation they were quite successful, although not always entirely in agreement. However, these early workers gave little attention to the chemical and physical properties imparted to the coal by the various plant components. Such investigations have been made in comparatively recent years.

[1] Address delivered at the Fiftieth Anniversary Celebration of the University of Chicago, September, 1941. Published by permission of the director, Bureau of Mines, United States Department of the Interior. Contribution from the Central Experiment Station, Bureau of Mines, Pittsburgh, Pa.

[2] H. G. A. Hickling, "William Hutton's 'Observations on Coals,' 1833," *Trans. Inst. Min. Engineers*, Vol. XC, Part IV (1935–36), pp. 243–53.

In the past decade European and American coal petrologists have done much toward clarifying the relationship between microstructure of coal and its chemical and physical properties; it now becomes more and more apparent that microstructure must be considered whenever differences in coal properties are to be explained. In this paper some of the correlations between microstructure and the chemical, carbonization, and hydrogenation properties of coal are discussed.

RANK AND TYPE OF COAL

Anyone who attempts to study the behavior of coal should have clearly in mind that the chemical and physical properties vary with both *rank* and *type*. The rank of a coal is determined by its position in the continuous and progressive series of carbonaceous solids that range from low-rank peats, through lignites, subbituminous coals, bituminous coals, and semianthracites to the high-rank anthracites. An increase in rank is marked by loss of moisture, oxygen, and volatile matter and by increase of carbon. It depends on the extent of metamorphism—the degree to which such factors as pressure, heat, and time have acted upon the coal bed. The type of coal is determined by the different blends of plant constituents and the extent of biochemical changes in the peat stage of coal formation. The common types of coal are known as "bright coal," "semisplint," "splint," "cannel," and "boghead." These types are found in all ranks of coal but always have attracted the most attention in coals of bituminous and subbituminous rank.

PETROGRAPHIC TYPES OF COAL

Determination of the petrographic types of coal by the Bureau of Mines is based on the method developed by Dr. Reinhardt Thiessen and depends on the kind and quantity of plant remains observed in thin sections of coal.

The bright coals comprise the greater part of our coal reserves and are sometimes referred to as "common banded coals." In the lump (Fig. 1) one can usually detect numerous bright (anthraxylon or vitrain) bands, and in the thin section the bright bands are seen to be separated by a translucent groundmass (Fig. 2). The groundmass

FIG. 1.—Typical lump of bright coal from No. 6 bed, Franklin County, Illinois.

FIG. 2.—Thin sections of bright coal illustrating anthraxylon bands separated by translucent attritus. ×100.

FIG. 3.—Lump of splint coal from Dorothy (Winifrede) bed, Kanawha County, West Virginia.

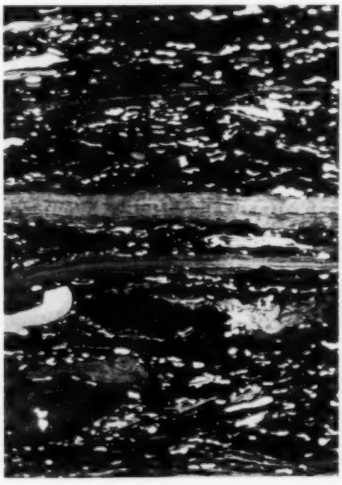


FIG. 4.—Cross section showing opaque ground mass of splint coals. ×100.

may consist of such translucent constituents as leaves, spores, resins, cuticles, or any translucent degradation matter.

Splint coals are of importance in West Virginia and Kentucky, particularly in beds of the Upper Pottsville formation. The splints have a dull luster, grayish-black color, and compact structure. They are hard and tough and break with an irregular, rough, sometimes splintery fracture into large lumps and slabs (Fig. 3). They are easily identified by thin sections, since they are characterized by a semiopaque to opaque groundmass, as in Figure 4, whereas the bright-coals sections have a groundmass that is predominantly translucent. Bright coals grade into semi-splints and then splints, as the amount of opaque constituents increases.

FIG. 5.—View showing blocky structure, conchoidal fracture, and nonbanded appearance of cannel coal.

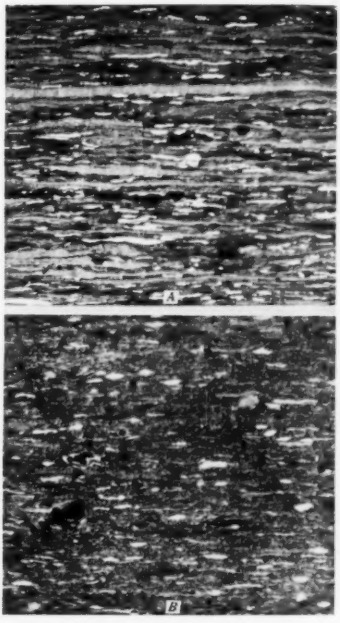


FIG. 6.—*A:* Cross section of a cannel composed largely of fragmented woody debris. Some opaque matter and a few spores are distributed throughout the mass. ×100. *B:* Cross section of an extremely high volatile spore-cannel coal. The smallest bright particles are pollen grains. ×100.

Cannel and boghead coals are clean, compact, block coals of massive structure and of uniform, fine-grained texture. They are usually

dark gray to black, have a greasy luster, and are noticeably of conchoidal or shell-like fracture. Figure 5 shows that a typical cannel has no sign of banding, for which reason they are classed as nonbanded coals. Thin sections under the microscope reveal that cannels are composed almost entirely of microdebris (Fig. 6), which may consist of a wide variety of constituents, such as spores, resins, woody fragments, and opaque constituents. Boghead coals differ microscopically from the cannels in that they contain large masses of oil algae (Fig. 7).

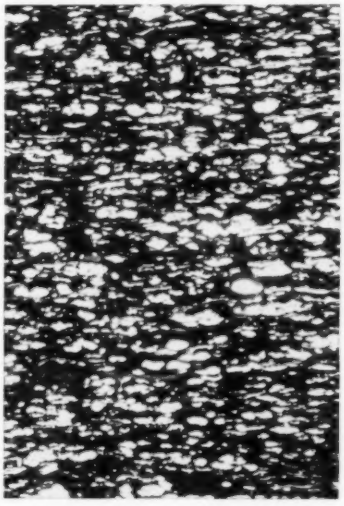


FIG. 7.—Cross section of a boghead coal. The irregular light patches represent oil algae, which are of a yellowish color in the original thin section. ×100.

CHEMICAL ANALYSES OF TYPES OF COAL

BRIGHT AND SPLINT COALS

In connection with a survey of gas-, coke-, and by-product-making properties of American coals the Bureau of Mines has obtained considerable data on the properties of the types of coals, particularly splint and bright coals. These data are discussed in detail in a Bureau of Mines technical paper.[3] Samples of splints were separated from column samples of seventeen different coal beds. These specimens were chemically analyzed; they were tested for agglutinating values and also for yield of coke and by-products by the Fischer low-temperature assay. Duplicate tests were made on samples of bright coal selected from the same beds, so that the effect of type and rank could be studied more carefully throughout the range of coking coals. It should be pointed out that splint coal is usually associated

[3] G. C. Sprunk *et al.*, "Splint Coals of the Appalachian Region: Their Occurrence, Petrography, and Comparison of Chemical and Physical Properties with Associated Bright Coals," *Bur. Mines Tech. Paper 615* (1940). Pp. 59.

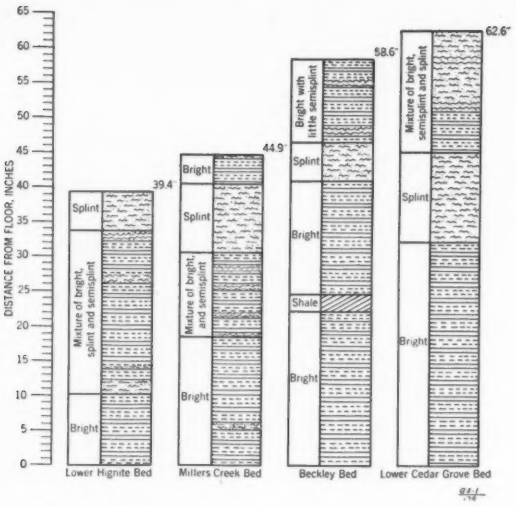


FIG. 8.—Distribution of coal types in column samples

TABLE 1

COMPARISON OF COMPOSITION OF 17 PAIRS OF BRIGHT AND SPLINT COALS FROM THE SAME BEDS

Composition	Bright Coals (Number Having Higher Value)	Splint Coals (Number Having Higher Value)	Equal Values
Moisture (as-received basis)	13	2	2
Ash (as-received basis)	3	14	0
Volatile matter (moisture-free and mineral-matter-free basis)	11	6	0
Hydrogen (moisture-free and mineral-matter-free basis)	13	2	2
Carbon (moisture-free and mineral-matter-free basis)	0	17	0
Nitrogen (moisture-free and mineral-matter-free basis)	14	0	3
Oxygen (moisture-free and mineral-matter-free basis)	14	2	1
Calorific value (moisture-free and mineral-matter-free basis)	6	11	0
Softening temperature of ash	3	10	3

with several layers or bands of bright and semisplint coal. This distribution of coal layers is illustrated in Figure 8. Table 1 summarizes the comparative analyses of splint and bright coals.

In all instances the splint coals have a higher carbon content than the bright coals of the same beds, and generally they have a higher ash content, higher ash-fusion temperature, and higher calorific value. On the other hand, the bright coals generally have the higher moisture, hydrogen, nitrogen, and oxygen values.

TABLE 2

CHEMICAL ANALYSES OF RESINS AND SPORES

Sample	As Received		Moisture-free and Ash-free Basis							
			Proximate		Ultimate					Calorific Value (B.t.u. per Pound of Coal)
	Moisture	Ash	Volatile Matter	Fixed Carbon	H	C	N	O	S	
Resin from coal (Merritt, British Columbia)	0.5	1.8	96.1	3.9	10.2	83.6	0.3	5.7	0.2	17,270
Resin from coal (Carbon County, Utah)	0.4	3.5	94.3	5.7	10.4	85.6	0.4	3.2	0.4	17,910
Spores from coal (Ingham County, Michigan)	2.0	9.8	76.6	23.4	7.6	80.6	1.0	9.4	1.4	15,350

Although Table 1 indicates that most of the bright coals give the higher percentage of volatile matter, it may vary in either direction, depending on the exact composition of the bright or splint coals, that is, whether they are spore-rich, resin-rich, etc. The fact that the presence of spores and resins will increase the volatile-matter content is illustrated in Table 2, which gives the analyses of resins separated from a British Columbia coal and from a Utah coal. The spores are from a Michigan spore coal.[4]

Spores in splint coal tend to offset the low volatile content of the opaque to semiopaque constituents, so that such a coal may have a

[4] Sprunk, Selvig, and Ode, "Chemical and Physical Properties of Spores from Coal," *Fuel in Sci. and Pract.*, Vol. XVII (1938), pp. 196–99.

proximate analysis similar to that of anthraxylon or bright coal of the same bed. If the splint has no spores or few spores, it usually will have 3–15 per cent less volatile matter than the accompanying bright coal. An example of such a splint is the Stockton-Lewiston (see Table 3), which has 26.0 per cent volatile matter (dry, ash-free coal basis), whereas the bright coal from the same column sample contains 39.3 per cent volatile matter.

If the total carbon is considered as an indication of rank, all the splints would be higher in rank than the associated bright coals.

TABLE 3

ANALYSES OF SPLINT AND BRIGHT COAL, STOCKTON-LEWISTON BED, KANAWHA COUNTY, WEST VIRGINIA

Sample	As Received		Moisture-free and Ash-free Basis							
			Proximate		Ultimate					Calorific Value (B.t.u. per Pound of Coal)
	Moisture	Ash	Volatile Matter	Fixed Carbon	H	C	N	O	S	
Bright coal	2.3	3.8	39.3	60.7	5.5	84.7	1.6	6.8	1.4	15,130
Splint coal	2.1	9.8	26.0	74.0	4.4	87.4	1.5	6.1	0.6	14,890

Since it is believed that the opaque groundmass in splint coals is the result of a high degree of rotting in the peat stage, it would seem that the organic matter in the course of decomposition by biological agencies undergoes chemical changes that are in some respects similar to those caused by metamorphic processes, such as pressure and heat. Apparently, the opaque matter has undergone "devolatization" in the peat stage through loss of hydrogen, oxygen, sulphur, and nitrogen; and there was an enrichment of carbon as decay progressed, although some carbon undoubtedly was lost as carbon dioxide and methane. This statement agrees with the observations of David White and Reinhardt Thiessen:

> In some "mature peat" the organic matter in the course of decomposition under the biochemical process has become further deoxygenated than is the substance of some distinctly xyloid lignite that obviously is already somewhat

affected by the dynamochemical process. The seeming result is to develop in peat a calorific value greater than that of lignite on the same basis (dry "combustible" matter).[5]

It has been claimed that the properties of anthraxylon (vitrain) and not those of the whole coal should be made the basis of determining rank.[6] With the exception of the nonbanded cannel and boghead coals, anthraxylon usually can be separated in sufficient quantity for analysis. It is generally agreed that anthraxylon bands that

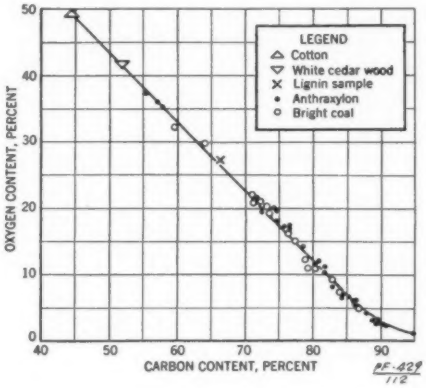


FIG. 9.—Relation between carbon and oxygen contents of anthraxylon and bright coals (moisture- and ash-free basis).

have been subjected to the same degree of metamorphism will have approximately the same ultimate and proximate analyses. Figure 9 shows that a linear relationship exists between the carbon and oxygen contents of approximately fifty anthraxylons and anthraxylous coals, ranging from peat to anthracite.[7]

It can be seen that there is still room for research and discussion on the rank of coal. It should be remembered that splint and cannel coals, in contrast with bright coals, are highly heterogeneous and,

[5] "The Origin of Coal," *Bur. Mines Bull. 38* (1913), p. 94.

[6] C. A. Seyler, "Petrology and the Classification of Coal," *Colliery Guard.*, Vol. CLV (1937), pp. 990–94, 1046–48, 1087–89, 1137–39.

[7] C. H. Fisher *et al.*, "Hydrogenation and Liquefaction of Coal," Part II: "Effect of Petrographic Composition and Rank of Coal," *Bur. Mines Tech. Paper* (in press).

therefore, that the carbon content, volatile-matter content, etc., are only average values for all the constituents present. For example, as judged by volatile matter, the anthraxylous portion of a coal might correspond to high-volatile bituminous coal in rank, whereas the rank of the opaque groundmass of the same coal may be similar to that of low-volatile bituminous coal.

CANNEL AND BOGHEAD COALS

Cannel coals show the widest range in chemical composition of the four main types of coal, and for this reason they have caused con-

TABLE 4

CHEMICAL ANALYSES OF CANNEL COALS AND OIL ALGAE

Sample	As Received		Moisture-free and Ash-free								Agglomerating Index
			Proximate		Ultimate					Calorific Value (B.t.u. per Pound)	
	Moisture	Ash	Volatile Matter	Fixed Carbon	H	C	N	O	S		
Spore cannel (Kentucky)	0.5	9.1	73.4	26.6	8.4	83.3	1.6	3.9	2.8	16,550	Very poor coking
Woody cannel (Pennsylvania)	0.6	5.3	43.5	56.5	6.0	85.5	1.8	5.0	1.7	15,520	Fair coking
Oil algae from oil shale	2.9	15.4	89.2	10.8	9.5	78.8	0.1	9.7	1.9	15,930	.....

siderable uncertainty in all schemes of coal classification. Their physical properties are well known, but no systematic study has been made that shows the relation between the microscopic composition of cannels and their chemical properties. A notion seems to persist that all cannels are rich in spores high in volatile matter and are non-caking; but the fallacy of this statement can be shown by comparing Figure 6, *B*, which illustrates a typical spore cannel, and Figure 6, *A*, which shows a typical woody cannel. Both have nearly the same physical properties, but the chemical and caking properties are vastly different (see Table 4).

CORRELATION OF SMALL-SCALE LABORATORY COKING TESTS WITH MICROSCOPIC COMPOSITION OF COAL

METHOD OF TEST

Low-temperature carbonization tests have been useful in correlating the microscopic composition of coals with their coke- and by-product-making properties. Results of the low-temperature assays on splint coals and associated bright coals have been published.[8] The low-temperature carbonization assays were made by a modification of a method described by F. Fischer and H. Schrader.[9] By this method, 50 grams of air-dried coal passing a No. 20 sieve is carbonized at temperatures gradually increasing to 500° C. in a cast-aluminum retort, with recovery of coke, tar, water, light oil, and gas. The temperature of the retort is raised to a maximum of 500° C. in about 50 minutes, and heating is continued at 500° C. until the gas evolution is not more than 25 milliliters per 10 minutes. A detailed description of the apparatus, procedure, and evaluation of the test has been published.[10]

The yield, as obtained by the Fischer low-temperature carbonization assay, represents laboratory yield only. The factors that must be applied to convert them to commercial-plant yield would vary with each individual carbonization plant. The amount of tar obtained in commercial low-temperature plants usually is about 70 per cent of the Fischer assay yield, because the tar from the laboratory carbonization assay is removed quickly and less opportunity for secondary decomposition is permitted.

The yield of carbonization products of splint coals, with that of their associated bright coals, is summarized in Table 5. All the splint coals give a smaller amount of water of decomposition than their associated bright coals and in every instance but one a smaller yield of gas. The calorific value of the gas may vary in either direction, but the British thermal units of gas per pound of coal carbonized are

[8] Sprunk *et al.*, *op. cit.*

[9] "Crude-Tar Distillation with an Aluminum Distilling Apparatus," *Zeitschr. f. angew. Chem.*, Vol. XXXIII (1920), p. 172.

[10] Selvig and Ode, "Determination of Gas, Coke, and Byproducts of Coal: Evaluation of Laboratory Assay Tests," *Indust. Eng. Chem.*, Vol. VII (Anal. ed., 1935), pp. 88–93.

nearly always less for the splint coals. The yield of coke and of tar and oil may vary in either direction for both types of coal. As will be shown later, these yields depend on the volatile-matter or fixed-carbon content of the coal, which has been shown to be variable. As illustrated in Table 6, constituents like spores and resins that have exceptionally high volatile contents will also yield large quantities of tar and oil.

TABLE 5

COMPARISON OF YIELD OF 17 SPLINT COALS WITH ASSOCIATED BRIGHT COALS

Carbonization Yield	Bright Coals (Number Having Higher Value	Splint Coals (Number Having Higher Value	Equal Values
Coke (dry, mineral-matter-free basis)	6	11	0
Tar and oil (dry, mineral-matter-free basis)	10	7	0
Water (dry, mineral-matter-free basis)	17	0	0
Gas (dry, mineral-matter-free basis percentage)	16	1	0
Gas volume (dry, mineral-matter-free basis)	16	1	0
Gas (B.t.u. per cubic foot)	10	7	0
Gas (B.t.u. per pound of dry, mineral-matter-free coal)	15	1	1

TABLE 6

LOW-TEMPERATURE CARBONIZATION ASSAY YIELD OF SPORES RESINS, AND OIL ALGAE, DRY, ASH-FREE BASIS

Carbonization Yield	Spores from Michigan Spore Coal	Resins from British Columbia Coal	Oil Algae from Oil Shale
Carbonized residue (pounds per ton)	884	154	316
Tar and oil (gallons per ton)	101	200	175
Gas (cubic feet per ton)	2,790	2,070	2,110

A typical high-volatile bituminous coal similar to that at the Bureau's experimental mine in Allegheny County, Pennsylvania, will yield about 35–40 gallons of tar and light oil per ton.

LOW-TEMPERATURE COKE

The low-temperature coke yield ranged from 71 per cent for a high-volatile bituminous coal to 95 per cent for a low-volatile bituminous coal. Figure 10 shows the yield of low-temperature coke plotted against the percentage of fixed carbon in the coal, both on the dry, mineral-matter-free coal basis. The coke yield increases

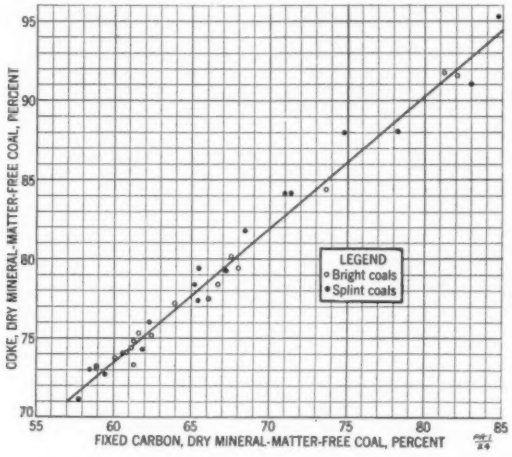


FIG. 10.—Relation of yield of low-temperature coke and fixed carbon content of bright and splint coals, dry, mineral-matter-free coal basis.

regularly with increase in fixed-carbon content of both splint and bright coals.

The straight line drawn on the graph in Figure 10 gives the following relationship:

$$\text{Coke, percentage} = (0.836 \times \text{fixed carbon, percentage}) + 23.4 . \quad (1)$$

The equation applies equally well to both splint and bright coals of bituminous rank; therefore, the fixed-carbon content of the coal determines the coke yield, regardless of the type of coal carbonized.

Figure 11 shows coke residues from splint and bright coals of considerable range in rank. The cokes from the higher-rank bituminous bright coals are considerably more swollen and cellular than those from splint coals. The cokes from bituminous bright coals of lower

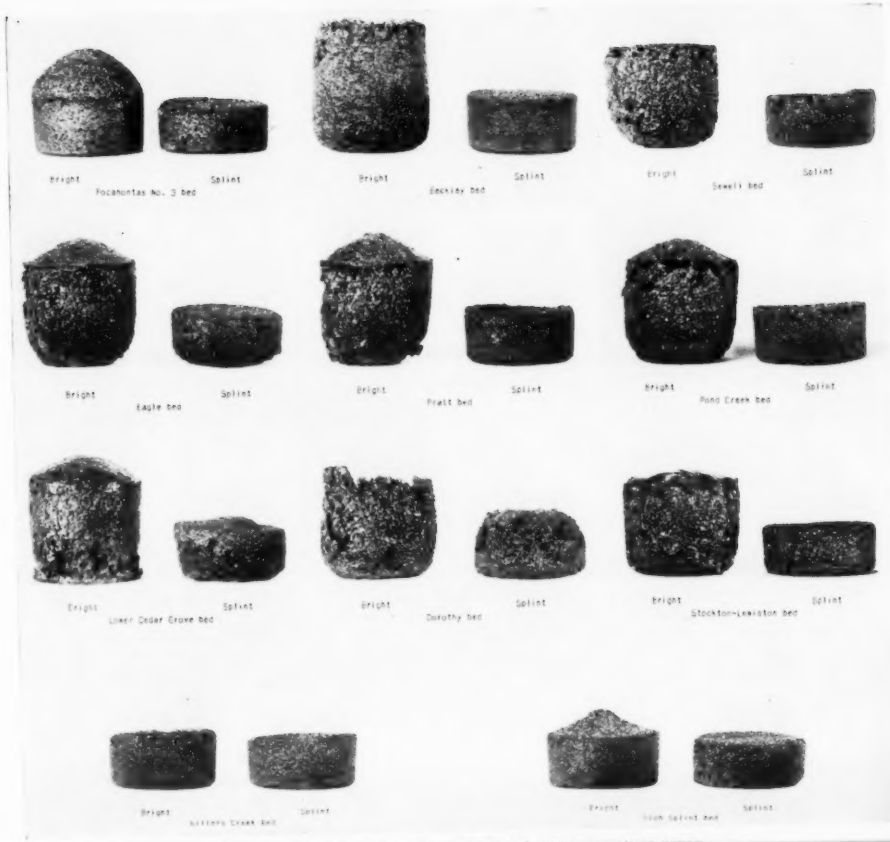


FIG. 11.—Coke residues from Fischer low-temperature assay

rank are similar in physical properties to the cokes from the splint coals from the same coal bed (see bottom row, Fig. 11). In fact, the coke from the Millers Creek splint coal is slightly harder and less friable than that from the associated bright coal; this is confirmed by the higher agglutinating value of the splint coal. R. A. Mott,[11] in his studies on the coking properties of durain, states that in bituminous coals of lowest rank, coke made from durain is better than that made from bright coals.

LOW-TEMPERATURE TAR AND OIL

Figure 12 shows the relationship between tar and oil yield and the volatile-matter content of bright and splint coals. The equations de-

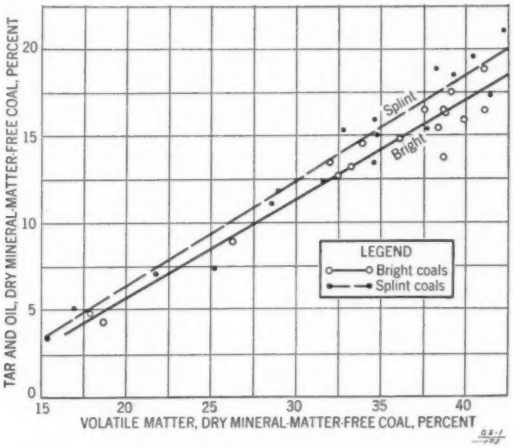


FIG. 12.—Relation between tar and oil and volatile matter

rived from these graphs for the calculation of tar and oil yield from the volatile-matter content of these coals are as follows:

For bright coals Tar and oil, percentage = 0.571 (volatile matter, percentage − 10.1). (2)

For splint coals Tar and oil, percentage = 0.605 (volatile matter, percentage − 9.6). (3)

[11] "Studies in Coke Formation: The Coking Properties of Durain," *Fuel in Sci. and Pract.* Vol. XIII (1934), pp. 356–65.

The maximum difference between the determined tar and oil yield and that obtained by calculation from equations (2) and (3) is 2.5 per cent.

If the volatile-matter content is reduced by an amount equal to 1.3 times the oxygen content of the coal, better correlation with the yield of tar and oil is obtained, as is shown in Figure 13. This is true because most of the oxygen acts as an inert component as far as the yield of tar and oil is concerned; in other words, less tar and oil are

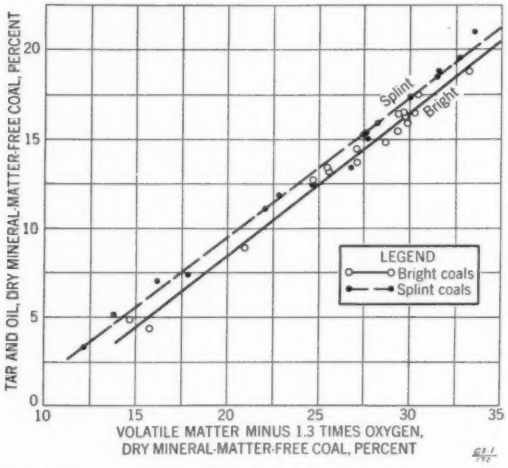


FIG. 13.—Relation between tar and oil and volatile matter *minus* 1.3 times oxygen

distilled from high-oxygen coals than from lower-oxygen coals of equal volatile-matter content.

The equations for deriving the yield of tar and oil from Figure 13 is as follows:

For bright coals Tar + oil, percentage = (0.805 × volatile matter, percentage) − (1.05 × oxygen, percentage) − 7.7 . (4)

For splint coals Tar + oil, percentage = (0.781 × volatile matter, percentage) − (1.02 × oxygen, percentage) − 6.2 . (5)

GAS

The effect of the type of coal on the yield of gas is pronounced. In every instance but one the volume of gas distilled from the bright

coal is greater than that from the associated splint coal. Attempts to correlate gas yields of bright and splint coals with their analyses have been productive of little information. In general, the yield of gas from the bright coals increases with increase in volatile-matter content; no such relationship, however, exists for the splint coals.

AGGLUTINATING VALUE OF BRIGHT AND SPLINT COALS

Agglutinating value was determined on each of the bright and splint coals by the Bureau of Mines agglutinating-value test.[12] In brief, the method of test consists of mixing finely ground coal with

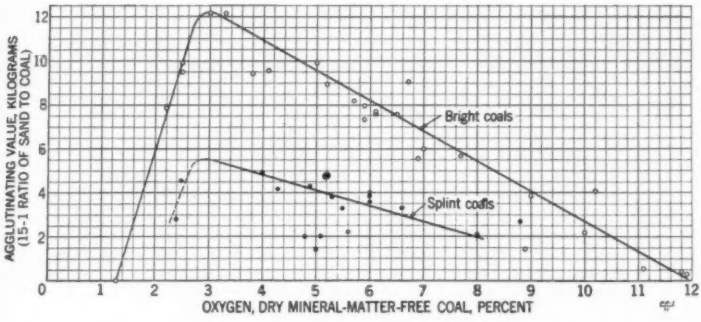


FIG. 14.—Relation of agglutinating value to oxygen content of bright and splint coals

sized Ottawa sand, compressing the mixture in a cylindrical crucible, and carbonizing for 20 minutes at 950° C. in an electrically heated furnace. The resulting carbonized button is then crushed in a compression testing machine; the crushing strength, expressed in kilograms, is taken as the agglutinating value at the particular sand-coal ratio selected.

The relationship of agglutinating value of bright and splint coals to their oxygen content is shown in Figure 14. For bright coals it may be seen that coals containing 3.0–3.3 per cent oxygen (dry, mineral-matter-free basis) have the maximum agglutinating value. The agglutinating value of coals containing less than this amount of oxygen decreases rapidly and regularly with decrease in the amount of

[12] W. A. Selvig, B. B. Beattie, and J. B. Clelland, "Agglutinating-Value Test for Coal," *Proc. Amer. Soc. Test. Materials*, Vol. XXXIII, Part II (1933), pp. 741–57.

oxygen. The agglutinating value of bright coals containing over 3.0–3.3 per cent oxygen decreases regularly with increase in oxygen content until it approaches zero for coals containing approximately 12 per cent oxygen.

The correlation of the oxygen content of splint coals with their agglutinating value is not good, although in general the agglutinating value decreases with increase in oxygen content.

EFFECT OF TYPE OF COAL ON PROPERTIES OF HIGH-TEMPERATURE COKES

Information on the properties of high-temperature cokes from the pure types of coal is quite meager. References in the literature give the general impression that the cokes from splint coal are inferior to those made from bright coals, although occasionally some statements appear that take the opposite view.

In the Bureau of Mines survey of gas- and coke-making properties of American coals, most of the cokes made from the coals containing large amounts of splint do not differ appreciably from the bright coals as far as shown by the tumbler and shatter tests. However, nearly all the coals with large amounts of splint were high-volatile bituminous coals.[13] Only one of the nine medium- and low-volatile coals examined contained more than 10 per cent splint, and thus it is unsafe to draw conclusions regarding the effect of splint on the coking properties of low- and medium-volatile coals—a group that includes many of our best coking coals.

Reynolds,[14] of the Bureau of Mines, has stated that certain carbonizing properties of medium-volatile coals are not predictable from chemical analyses and that petrographic composition may modify these properties more than has been recognized generally. Table 7 shows the petrographic composition and coking tests of four medium-volatile Appalachian coals.

[13] A. C. Fieldner and J. D. Davis, "Gas-, Coke-, and Byproduct-making Properties of American Coals and Their Determination," *Bur. Mines Mono. 5* (1934). Pp. 164. *Bur. Mines Tech. Papers 570, 571, 572, 584, 594, 595, 596, 599, 601, 604, 616, 621, 628; Bur. Mines Bull. 411.*

[14] D. A. Reynolds and J. D. Davis, "Coal Carbonization: Carbonization Properties of Medium-volatile Coals of Different Types" (paper presented at meeting of American Chemical Society, Atlantic City, September 8–12, 1941).

The Lower Freeport-, Bakerstown-, and Sewell-bed coals are predominately bright coals, but the Lower Banner contains considerable semisplint and cannel coal. The Lower Banner differs from the other three in that it gives the weakest coke as determined by both tumbler and shatter tests. The Lower Banner also differs in that it contracts during carbonization, whereas the others expand. The expansion properties of coals are given important consideration in selecting coals for coking, because it is often necessary to dilute highly ex-

TABLE 7

CARBONIZING CHARACTERISTICS AND PETROGRAPHIC COMPOSITION OF FOUR APPALACHIAN COALS

Coal	Dry, Mineral-Matter-Free Fixed Carbon (Percentage)	Types (Percentage)				900° Coke		Expansion in Sole-Heated Oven (Percentage)
		Bright	Semi-splint	Splint	Cannel	1½-Inch (Shatter Index)	1-Inch (Tumbler Index)	
Lower Freeport	73.4	93	5	2	0	88.9	69.8	+19.0
Lower Banner	76.9	36	53	0	11	82.6	65.4	− 6.2
Bakerstown	77.1	91	3	6	0	88.0	72.3	+ 9.8
Sewell	77.5	81	15	4	0	85.7	68.9	+16.0

panding coals with nonexpanding coals to prevent injury to certain types of coke ovens.

The study of the properties of high-temperature cokes from the pure types of coal is far from complete. There is great need for information on the coking properties of pure types of coal from all ranks of coal within the coking range. Such studies must be carefully correlated with physical properties of coke, plastic measurements, and coke structure.

HYDROGENATION PROPERTIES OF TYPES OF COAL AND THEIR CONSTITUENTS

The Bureau of Mines small-scale hydrogenation tests on the banded constituents of coal have led to the general conclusion that bright coals are more suitable than splint coals for conversion into liquid

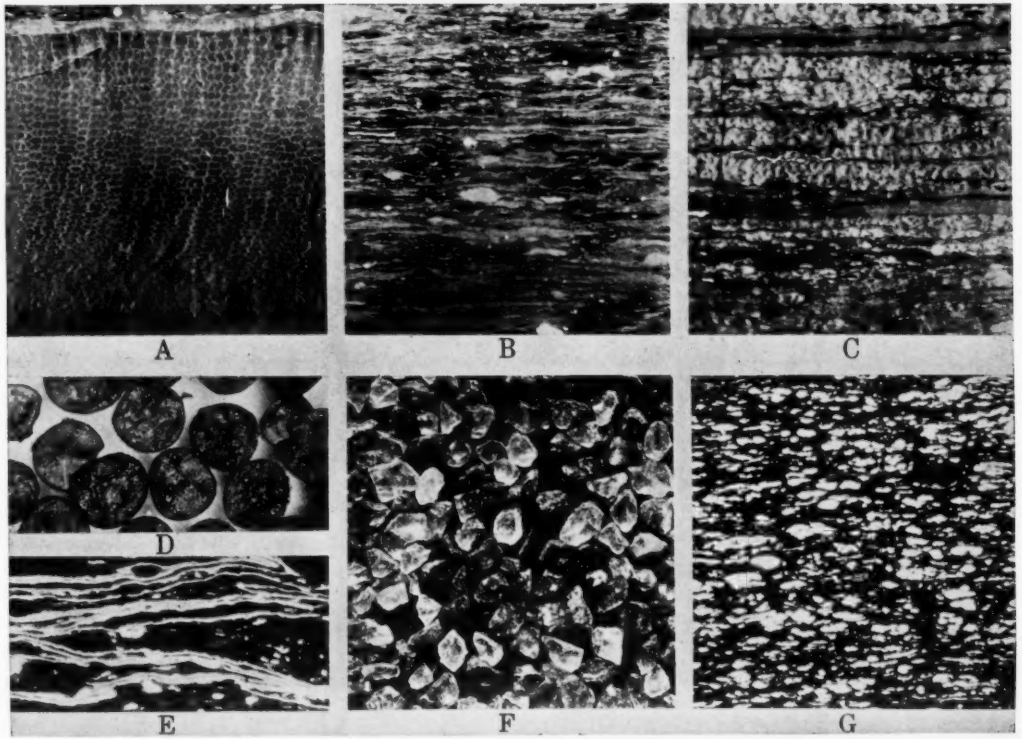


FIG. 15.—Coal constituents that are easily liquefied in the small-scale hydrogenation tests: *A*, anthraxylon; *B*, woody degradation material; *C*, leaf residue; *D*, spores; *E*, cuticles; *F*, resins; *G*, oil algae.

products. Details of the test procedure and the results obtained by the Bureau of Mines small-scale hydrogenation tests have been given in other papers.[15]

The hydrogenation results indicate that, with respect to liquefaction yield, the coal constituents may be classed conveniently in two groups. The first group of easily liquefiable constituents, illustrated in Figure 15, includes anthraxlyon and all organic constituents of the translucent attritus, such as woody degradation matter, leaves, spores, pollens, cuticles, resins, and algae. This statement applies to coals containing less than 89 per cent carbon (moisture-free and ash-free basis); additional data are required to determine the hydrogenation characteristics of the above constituents in extremely high-rank coals known to give lower liquefaction yield.

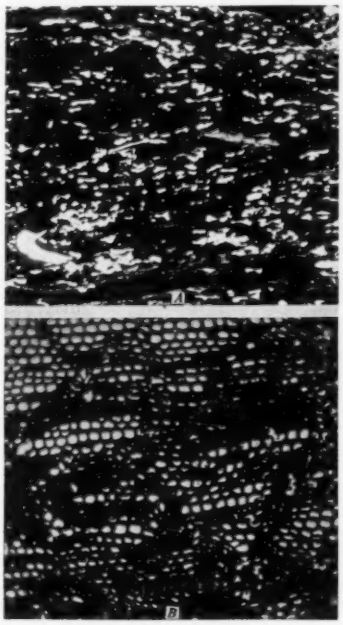


FIG. 16.—Coal constituents difficult to liquefy in small-scale hydrogenation tests: *A*, opaque attritus (×100); *B*, fusain (×75).

The second group of constituents (see Fig. 16) is more difficult to liquefy. One of the constituents is opaque attritus, the characterizing constituent of splint coals; the other is fusain. Data from twelve

[15] C. H. Fisher *et al.*, "Hydrogenation of the Banded Constituents of Coal: Fusain," *Indust. Eng. Chem.*, Vol. XXXI (1939), pp. 190–95; "Hydrogenation of Spores, Resins, and Other Attrital Constituents of Coal," *Fuel in Sci. and Pract.*, Vol. XVIII (1939), pp. 132–41; "Hydrogenation of Anthraxylon from Bituminous Coals," *ibid.*, pp. 196–203; "Hydrogenation of the Banded Constituents of Coal: Attrital Matter and Anthraxylon," *Indust. Eng. Chem.*, Vol. XXXI (1939), pp. 1155–61; A. Eisner *et al.*, "Hydrogenation of Typical Splint Coals," *Indust. Eng. Chem.*, Vol. XXXII (1940), pp. 73–78.

splint samples show that the average liquefaction yield of opaque attritus is about 60 per cent when hydrogenated at 430° C. for 3 hours in the presence of stannous sulphide and with initial hydrogen pressure of 1,000 pounds per square inch. The fact that there is considerable range in the degree of opacity explains the variation in yield, which is between 39 and 79 per cent for the individual samples. Hydrogenation of seven samples of fusain gave a liquefaction yield be-

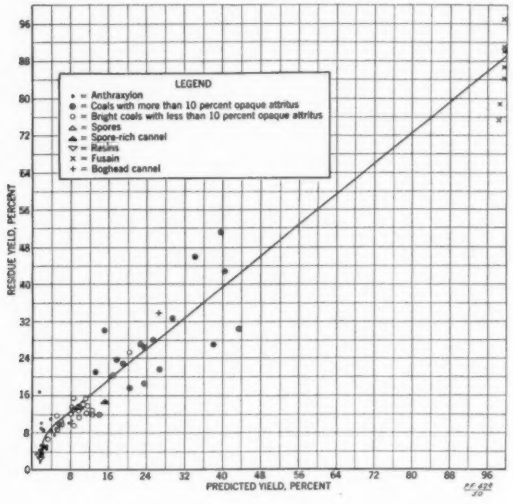


FIG. 17.—Yields of residue predicted from petrography

tween 15 and 27 per cent, which shows that this material is the most resistant of all coal constituents.

By means of petrographic methods the yield of residue can be predicted with fair accuracy. Figure 17 shows the yield of residue predicted from petrography plotted against the determined yield. The predicted yield was estimated by assuming that the different constituents would give the following percentage yield of residue: ash and fusain, 100; opaque attritus, 38; all other constituents, 0. Further examination points to the varying opacity of the opaque attritus as responsible for some of the more inaccurate predictions. For

example, a splint sample from the Chilton bed gave an exceptionally high liquefaction yield, in view of its apparent high content (80 per cent) of opaque matter. Microscopic examination showed that an unusually high proportion of the seemingly opaque matter was brown or semiopaque and therefore would be expected to hydrogenate more readily than attritus, which is more opaque.

TABLE 8

YIELD OF ORGANIC RESIDUE PREDICTED FROM MICROSCOPIC ANALYSIS COMPARED WITH THOSE OBTAINED IN THE EXPERIMENTAL PLANT

ORIGIN OF COAL		CARBON CONTENT (PERCENTAGE)	RESIDUE (PERCENTAGE OF DRY COAL)	
State	Bed or Mine	Moisture- and Ash-free Basis	Predicted*	From Plant Assay
Alabama	Mary Lee	86.9	9.0	9.8
Pennsylvania	Pittsburgh	84.2	7.8	4.0
Illinois	No. 6	80.6	5.4	4.9
Washington	McKay	78.6	0.5	1.1
Colorado	Puritan	76.6	8.0	5.6
Montana	Rosebud	76.7	8.2	6.7
Wyoming	Monarch	75.6	2.6	3.1
North Dakota	Buelah	73.0	7.6	9.7
North Dakota	Velva	72.0	6.6	4.7

* From microscopic examination.

By means of microscopic examination of coal considerable success has been attained in selecting the best coals for the large-scale hydrogenation tests. In Table 8 comparison of the yields of residue calculated from the microscopic composition and of those actually obtained by continuous hydrogenation shows that the microscopic examination is a useful tool for predicting the approximate yields of inert residues.[16]

[16] H. H. Storch *et al.*, "Hydrogenation and Liquefaction of Coal," Part I: "Review of Literature, Description of Experimental Plant, and Liquid-Phase Assays of Some Typical Bituminous, Subbituminous, and Lignitic Coals," *Bur. Mines Tech. Paper 622* (1941). Pp. 110.

It is of interest to note that the large-scale hydrogenation tests on the McKay-bed coal led to the following conclusions:

> The high-volatile C coal from King County, Washington, hydrogenated easily with no operating difficulties whatever. This coal was in many respects the most desirable raw material for hydrogenation thus far used in our plant-assay work on United States coals. Its desirable qualities are low ash, almost no fusain and little opaque attritus, low viscosity of the heavy-oil product, and low yield of gas.[17]

In order to select other suitable coals for large-scale hydrogenation tests a rather extensive investigation of the western low-rank coals has been carried out. Samples from more than fifty coal beds in Colorado, Montana, New Mexico, North Dakota, Oregon, Utah, Texas, Washington, Wyoming, and Alaska were examined. The survey has shown that this area contains tremendous reserves of coal that are well suited for conversion to liquid fuels by the hydrogenation process, and therefore they should constitute a large potential source of liquid fuels and organic chemicals when the petroleum supply fails to meet the demand.

SUMMARY AND CONCLUSIONS

1. A discussion of the correlation between microstructure and the chemical, carbonization, and hydrogenation properties of coal has shown that microstructure must be considered whenever differences in coal properties are to be explained.

2. The type of coal and the kind of constituents have considerable effect on the ultimate and proximate analysis. When compared on the dry, mineral-matter-free coal basis, the splint-coal layers selected from seventeen different coal beds have a higher carbon content than the bright coals of the same beds. Generally they have a higher ash content and a higher ash-fusion temperature. The bright coals generally have the highest moisture, hydrogen, nitrogen, and oxygen values and the lowest calorific values. The volatile-matter content may vary in either direction, depending on the petrographic composition of the bright or splint coal. Components such as spores and resins give an unusually high yield of volatile matter. Cannel coals

[17] *Ibid.*

show the widest range in chemical composition of the four main types of coal, owing to their variability of microscopic composition.

3. The yield of carbonization products from the splint and bright bituminous coals was determined by the Fischer low-temperature carbonization assay. On the dry, mineral-matter-free coal basis, each of the splint coals gives a smaller yield of water of decomposition, and in every instance but one a smaller yield of gas, than does its associated bright coal. The yield of coke and of tar and oil of splint coal may be higher or lower than that of bright coal, depending on the analyses of the coals. Likewise, the calorific value of the gas may vary in either direction, but the B.t.u. of gas per pound of coal carbonized is nearly always less for the splint coals. Except for the coals of higher oxygen content, the coke residue from the bright coals is considerably more swollen and cellular than that from the splint coals.

4. The following relationships have been established between the analyses of the coals and the yields of carbonization products, all on the dry, mineral-matter-free basis:

a) The fixed carbon content of the coal determines the yield of coke, regardless of the type of coal carbonized.

b) The tar and oil yield increases quite regularly with increase in volatile-matter content of the splint and bright coals. A better correlation of tar and oil yield is obtained if the volatile-matter content is reduced by an amount equal to 1.3 times the oxygen content of the coal. The tar and oil yield increases with increase in hydrogen content of both the splint and the bright coals, the yield for coals of equal hydrogen content being greater for the splint coals than for the bright coals.

c) Attempts to correlate the gas yield of the bright and splint coals with their chemical analyses have provided little information. In general, for the bright coals, the yield of gas and the B.t.u. of gas per pound of coal increase with increase in the volatile-matter content of the coal.

5. The oxygen content of bright coals correlates well with the agglutinating value of the coal. Bright coals of 3.0–3.3 per cent oxygen (dry, mineral-matter-free coal basis) have the maximum agglutinating value, the values decreasing with increase or decrease in the amount of oxygen. The correlation with the oxygen content of the splint coals is not good, although in general the agglutinating value decreases with increase in oxygen content.

6. The study of the properties of high-temperature cokes from the pure types of coal is far from complete. There is a great need for information on the coking properties of pure types of coal from all ranks of coal within the coking range.

7. The Bureau of Mines small-scale hydrogenation tests on the banded constituents of coal have led to the general conclusion that bright coals are more suitable than splint coals for conversion into liquid products.

ACKNOWLEDGMENTS.—The author takes pleasure in acknowledging his indebtedness to W. A. Selvig, supervising chemist, coal constitution and miscellaneous analysis section of the Bureau of Mines, who directed the investigation reported herewith.

PHYSICAL CONSTITUTION OF COAL AS RELATED TO COAL DESCRIPTION AND CLASSIFICATION[1]

E. C. DAPPLES
Northwestern University

ABSTRACT

Present-day classification of coals places a marked boundary between banded and nonbanded varieties. In banded coals the principal physical constituents are visibly distinct. Now banded coals need not be considered a separate group, since cannel is gradational into durain and durain grades into "bone coal." Despite their megascopic appearance as separate entities, the units of banded coals are closely interrelated. Such constituents increase in rank with progressive metamorphism and show a corresponding change in appearance.

INTRODUCTION

Mineral fuels as sources of heat and power have for centuries attracted the attention of men interested in the utilization of their energy. Some of the properties associated with the release of such energy were recognized at an early date, for the combustion of coal and the residue of ash which remained were described in the writings of Theophrastus (371 B.C.).[2] It is surprising, therefore, in view of the long knowledge of its existence, its common occurrence, and its widespread usage, that so little interest has been directed toward an understanding of the physical constitution of coal as an aid in coal description and classification. Recognition of banding and differences in luster had been recognized by miners before the nineteenth century, and Henry Witham (1831) was the first to describe the microscopic appearance and note the organic origin of some of the constituents of English coals.[3] Such observations of a paleobotanical nature indicate the character of the knowledge of the constitution of coal up to the time that David White and Reinhardt Thies-

[1] Address delivered at the Fiftieth Anniversary Celebration, University of Chicago, September, 1941.

[2] H. N. Eavenson, *Coal through the Ages* (New York: American Institute of Mining Engineers, 1935), pp. 3–4.

[3] Reinhardt Thiessen, "Structure in Paleozoic Bituminous Coals," *U.S. Bur. Mines Bull. 117* (1920), p. 3.

sen[4] described its microscopic structure in detail. In 1914 these investigators proposed the modern interpretation of the nature of the banded ingredients as fragments of former wood and finely divided plant debris. Later two systems of terminology to be used in coal description were introduced, that of M. C. Stopes,[5] based upon the megascopic appearance of the coal laminas, and that of Thiessen,[6] founded upon the principle that certain parts of plants produced two unique coal substances.

The systems of Stopes and Thiessen have dominated coal description since their proposal. Thiessen regarded anthraxylon and attritus as primary coal constituents, each possessing characteristic physical and chemical properties and each directly controlling the properties of the composite coal of which they form a part. Likewise, he recognized that fragmental organic material develops two varieties of attritus, each of which is associated with a distinct type of coal. The lucid attrite dominates the attritus in the humic or anthraxylous coals, whereas the opaque attrite is associated with certain coals known as "splints." All gradations exist between coals consisting entirely of anthraxylon and those consisting entirely of attritus.[7]

The classification prepared by Stopes, being based upon physical properties, designates four coal types—vitrain, clarain, fusain, and durain—and provides a means of field description of a composite coal. In 1935 Stopes[8] expanded the system of terminology and reclassified vitrain, clarain, fusain, and durain as rock types. Each rock type is composed of macerals (equivalent to minerals in rocks), such as vitrinite, fusinite, exinite (spore exines, cuticles, etc.), and micronite—the last a granular, colloidal coal substance, opaque to transmitted light. Stopes's classification was accepted with some

[4] "Origin of Coal," *U.S. Bur. Mines Bull. 38* (1914).

[5] "On the Four Visible Ingredients in Banded Bituminous Coal," *Proc. Roy. Soc. London*, Vol. XC (1919), pp. 470–87.

[6] "Research in the Constitution of Coal," *Ill. Geol. Surv. Bull. 60* (1930), pp. 117–31.

[7] *Ibid.*, p. 122.

[8] "On the Petrology of Banded Bituminous Coals," *Fuel in Sci. and Pract.*, Vol. XIV (1935), pp. 4–13.

modification by the Second International Conference on Carboniferous Stratigraphy at Heerlen (Netherlands) and recommended for general use.

THE PRIMARY COAL TYPES

BANDED AND NONBANDED COALS

The most striking characteristic of certain so-called "mature" coals is their striped or banded appearance. This laminated structure, in which vitrain bands alternate with bands of clarain, fusain, and durain, is not universally present in all coals. It is inconspicuous in some and entirely absent in others, and, as a consequence, there has arisen a subdivision of all coals into banded and nonbanded varieties. Among the banded coals a continuous series in rank is recognized to exist from lignite through anthracite. No such series is recognized for the nonbanded coals, which, because of the lack of banding and some differences in chemical properties, have been established as a distinct group. Such coals of homogeneous composition are local in occurrence and irregular in distribution but commonly form a bench in a bed of banded coal. No complete series of progressive metamorphism has been described for these boghead or cannel coals, and hence they are omitted entirely from some systems of coal classification and not properly placed in the one most recently proposed.[9]

Since the differentiation of coals into banded and unbanded varieties is generally accepted and used in descriptions, consideration of the so-called "ingredients" that compose all coals is pertinent to the question regarding the establishment of boundaries between banded and nonbanded coals. Investigators now hold the concept that vitrain, fusain, clarain, and durain are fundamental coal types and that all banded coals are composites of two or more such types. Since each of the primary coals has its characteristic physical and chemical properties, the relative proportions of the primary coals constituting a composite coal control the properties of the latter.

[9] American Society for Testing Materials, "Tentative Specifications for the Classification of Coal by Rank, Designation D 388–34T" (1934).

Other properties inherent in composite coals are those which result from the change brought about in any of the primary coals by the influence of metamorphism. Thus a lignite or a bituminous coal is a composite of several primary coals and indicates a stage of progressive metamorphism rather than a coal variety.

VITRAIN

The effect of metamorphism is more readily recognized in vitrain than in any other primary coal. Thiessen[10] demonstrated that vitrain was derived from fragments of wood, whereas other primary coals were formed from plant degradational material. Through a process, the mechanism of which is as yet unknown, the xyloid material becomes transformed into vitrain. Descriptions of vitrain are based upon that present in mature coals. In immature composite coals, such as black lignite, vitrain may be distinguished from other primary coals by its somewhat brighter luster; but the brilliance which characterizes the luster in subbituminous and bituminous coals is lacking, and the identification of vitrain as distinct from clarain is not always certain. In anthracites the brilliance of vitrain is increased over that in bituminous coals, and the luster can be described as submetallic. Such a change is characteristic of anthracitization. Accompanying the appearance of the submetallic luster is a radical change in the optical properties of the vitrain. It is no longer translucent under transmitted light but is opaque. The increase in the brilliancy of the vitrain with increase in rank is a well-established fact and has been demonstrated to be independent of the presence of any particular variety of plant.[11]

Variations in luster are not, however, entirely the result of differences in the rank of the coal, for vitrains of the same rank may differ in luster—those containing resinous bodies (resinite) possessing higher luster than vitrains, which lack them. Resins, waxes, and xyloid material are very sensitive to changes in temperature and pressure and become darker with an increase in refractive index as

[10] "Structure in Paleozoic . . . . ," *op. cit.*, pp. 42–44.

[11] L. C. McCabe, "Some Physical Evidence of the Development of Rock in Vitrain," *Fuel in Sci. and Pract.*, Vol. XVII (1937), pp. 267–79, 309–16.

the rank of the coal increases.[12] Waxes are particularly unstable, and in the process of anthracitization they may volatilize or decompose.[13] The sensitivity of the luster of the vitrain appears to be related, therefore, to the instability of the resins, waxes, and xyloid material and to their tendency to form a new vitrain of slightly different physical properties under the new conditions of temperature and pressure.

The differentiation of the varieties of vitrain as proposed by Stopes[14]—particularly to distinguish between that which is structureless and that which shows the former structure of wood—is impossible megascopically and seems undesirable even microscopically, since, as far as is known, the physical and chemical properties remain identical for the two vitrains. Since vitrain is so sensitive to changes in physical conditions and does reflect the rank of the composite coal, the knowledge which is essential to the coal petrographer is not the presence or absence of cellular structure but rather the maceral composition of the vitrain and its rank as indicated by luster. If both the constitution of the vitrain, particularly with respect to the resinite content, and its rank are known, its character is rather definitely established. It would be desirable, therefore, to have designated a standard scale of vitrains of various ranks in terms of their luster. In this connection the method devised by McCabe[15] of measuring refractive indices of vitrain is worthy of considerable attention, particularly with a view toward refinement of the technique.

FUSAIN

Identification of fusain in the field and laboratory is possible without difficulty, irrespective of the rank of the coal. Fusain has the same appearance in lignites as in low-volatile bituminous coals. Under the conditions of anthracite formation, however, fusain loses its fibrous texture, and its luster increases in brilliance until it

[12] D. J. Fisher, "Coal Composition," *Amer. Min.*, Vol. XIX (1934), p. 133; Dapples, "Resins and Waxes in Colorado Coals," *Trans. Ill. Acad. Sci.*, Vol. XXXI (1938), p. 176.

[13] Dapples, "Coal Metamorphism in the Anthracite-crested Butte Quadrangles, Colorado," *Econ. Geol.*, Vol. XXXIV (1939), pp. 387–88.

[14] "On the Petrology of . . . . ," *op. cit.*, Table, pp. 5–6.

[15] "Some Physical Evidence . . . . ," *op. cit.*, pp. 309–16.

approaches the uniform substance developed by all the primary coal types in the highest-rank anthracite.

Fusain has another property which distinguishes it from the other primary coals. Under certain conditions not as yet known but which appear to obtain chiefly in the production of coals of bituminous rank, fusain is gradational with vitrain and assumes the translucency and luster of the latter. Such material is designated as "semifusinite." In such instances the fusain appears to be low in inorganic mineral matter. More often it is high in content of inorganic material and when slightly weathered becomes plastic and develops the appearance of a dark-gray clay. Instances have been noted in anthracites when fusain maintains its dull luster, and in such cases it appears to contain much inorganic material.

Fusain in most composite coals is a minor constituent, but, because of its friability, low tensile strength, and its commonly high content of inorganic material, its presence must be carefully noted in all descriptions of composite coals. Most important, perhaps, is the nature of its occurrence as a more or less continuous band or in small irregular lenses, since in the first instance it always forms a plane of parting in the composite coal, whereas in the second instance it is not likely to form a plane of weakness.

DURAIN

Durain and clarain are primary coals, whose composition makes them distinct from vitrain and fusain. The former are clearly attrital coals formed from the degradational matter of all portions of the plants which contributed to coal formation. Since sufficient analyses of these two primary coals are now available to indicate their nature, the fact has been established that for any specific rank of coal the analyses of one of the primary coals differ from those of the other (Fig. 1). The variation is known to be produced by the percentage composition of the macerals which constitute the two.[16]

Durain as defined by Stopes[17] is a primary coal of compact tex-

[16] C. A. Seyler, "Petrology and Classification of Coal," *Fuel in Sci. and Pract.*, Vol. XVII (1938), pp. 179–86.

[17] "On the Petrology of . . . . ," *op. cit.*, Table, pp. 5–6.

ture, grayish-black matte luster, and containing micrinite and exinite. Thiessen[18] states that durain is similar to the American splint coal and to the German *Mattekohle*. The latter two coals, however, are definitely banded, consisting of vitrain bands alternating with a coal of dull-gray matte luster. Such zones in splint coal may consist

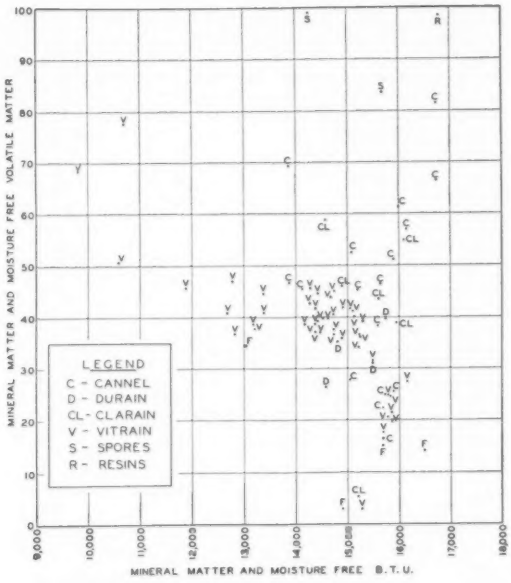


FIG. 1.—Published analyses of primary coals recalculated to the mineral matter and moisture-free basis, showing variations in composition resulting from differences in the proportion of organic constituents present.

entirely of micrinite and exinite.[19] Splint coal is, therefore, clearly a composite coal, and the term "durain" should be reserved for that primary coal type whose groundmass consists of micrinite. In limit-

[18] "What Is Coal?" (Cincinnati, Ohio: Appalachian Coals, Inc., 1937), p. 33.

[19] A. C. Fieldner *et al.*, "Carbonizing Properties and Petrographic Composition of High Splint Bed from Closplint Mine, Closplint, Harlan Co., Ky." *U.S. Bur. Mines Tech. Paper 599* (1939), pp. 5–7.

ing durain to such a primary coal, it is distinct from splint coals, which may contain more or less translucent material, such as vitrain and microvitrain.[20] Manifestly, since durain is a coal composed of degradational material, it should show much more variation in composition in any particular coal rank than vitrain, which, being derived from woody fragments, is more constant in composition.

Field identification of durain may be confused because of variations in appearance due to differences in rank or because of inherent mineral impurities. In lignites, durain is not megascopically recognizable, since its luster and physical appearance is identical with clarain. Hence, it is not reported as being associated with lignite, although its presence can be recognized microscopically by the groundmass of micrinite. Under progressive metamorphism the luster of durain increases in brilliance, but less so than either vitrain or clarain; hence it may be distinguished in the bituminous rank from vitrain and from most clarain by its dull-gray color, its conchoidal fracture, and its somewhat granular texture. In anthracites its luster increases until it becomes like that of other primary coals and thus loses its identity as a primary coal type. Certain exceptions exist in which durains are recognizable in anthracites because their luster has remained dull. All such instances examined by the author contain much inorganic material, nearly all of which is detritus.

The mineral matter which occurs in durain differs from that in fusain, since that present in the latter is a secondary deposit, whereas the mineral matter present in the durain is largely silt and clay deposited with the plant debris. All gradations exist between durains which contain much mineral matter and those in which no inorganic detritus is present. The detritus may be largely of clay dimensions and in many cases is megascopically not visible. In such instances its presence is noted by miners who recognize its resistance to combustion and describe it as "bone coal." Such bone coal is a rather commonly occurring substance and is found generally near the top or bottom of the coal stratum. Obviously, the amount of detrital silt and clay may be of sufficient proportion so that a carbonaceous

[20] Thiessen, "What Is Coal?" p. 33.

shale is formed. There exist, therefore, all gradations from carbonaceous shale to bone coal and from the latter to durain low in mineral matter. Each is characterized by the fact that most of the coaly material is in the form of micrinite, but minor amounts of other plant degradational matter, such as spore exines or cuticles, may be present also. The term "bone coal" may thus be reserved for a variety of durain sufficiently high in mineral matter that its combustion requires the addition of heat from an external source, yet which has, megascopically, more the appearance of a coal than of a carbonaceous shale.

CLARAIN

Clarain has been described as a primary coal type with a silky-gloss luster, consisting of thin or thick bands intrinsically stratified parallel with the bedding plane.[21] Often clarain appears striated owing to the presence of bands of microvitrain, which, when in laminas less than 0.05 millimeters, contributes to the development of the silky gloss. Clarain may be composed of a great variety of materials predominantly translucent and of small dimension, concentrated to various degrees; it may, therefore, show considerable variation in appearance. Because of the variability in appearance of clarain, there has been some uncertainty in regard to the correct application and even as to the usefulness of the name. Nevertheless, clarain has definite value as a term for megascopic field description of material representing a primary coal type. In a microscopic description it is important that the character of the clarain, particularly in terms of the attrital matter and microvitrain, be described. Descriptive terms for certain types of clarain, such as "duroclarite" and "teloclarite," unfortunately do not give a completely satisfactory picture of the clarain, since they present only a general description of the clarain composition.[22] The confusion over the use of the term "clarain" arose primarily because clarain was described on the basis of some of the most complex varieties present in mature coal

[21] Stopes, "On the Petrology of . . . . ," *op. cit.*, Table, pp. 5–6.

[22] W. J. Jongmans, R. G. Koopmans, and G. Roos, "Nomenclature of Coal Petrography," *Fuel in Sci. and Pract.*, Vol. XV (1936), pp. 14–15.

and the simple types were not recognized. There exist, however, varieties of coal which the author considers representative of clarain of simple maceral composition. Such clarain is represented by a group of nonbanded coals, namely, clarain-cannels.

CANNEL

The term "cannel" embraces several varieties of composite coal, some of which contain micrinite, whereas others are composed entirely of translucent attritus. Cannels of this last-mentioned variety are designated "clarain-cannels." Some of these cannels are composed of algal remains to the extent of nearly 90 per cent; others are nearly devoid of algae and are rich in spores.[23] Still other cannels are described, containing as much as 75 per cent resinous bodies and few spores.[24] Despite such differences in composition, the groundmass of such coal is composed of finely comminuted translucent attritus. The fine grain of such material distinguishes it from the more coarsely granular attritus of complex clarain, but other physical properties suggest that the two are identical and are translucent attritus or collinite. The simple nonbanded varieties of clarain possess certain physical characteristics which are imparted to other varieties of clarain. For example, clarain-cannel has a luster similar to dull, greasy silk, which may also increase in brightness to the color of dull, black silk, lacking the greasy luster, as the percentage of humic material is increased. The fine-grained texture appears to control the low friability and the conchoidal fracture which also characterize the coal. Cannel also has a tendency to "mine out" in rough cuboidal-shaped blocks. Such features, which are characteristic of cannel, appear to be due to the absence of microvitrain, to the fine subdivision of the translucent residuum, and to the common predominance of algite, sporinite, or exinite.

Certain cannels exist in which occasional bands of vitrain or microvitrain are also present. When such vitrain bands increase in num-

[23] G. A. Hickling, "Some General Aspects of Recent Research in Coal," *Fuel in Sci. and Pract.*, Vol. XI (1935), p. 327.

[24] I. W. Jones, "Microscopic Features of Certain Alberta Coals," *Fuel in Sci. and Pract.*, Vol. XVI (1937), p. 214.

ber so that they are numerous, the characteristics of common clarain appear. Microvitrain has a higher friability index than cannels; hence, the more the percentage of vitrain present in the translucent attritus of cannel is increased, the more friable the latter becomes. This depends somewhat upon the thickness and occurrence of the microvitrain lenses. If the vitrain is microbanded, that is, in thin shreds of 0.05–0.1 millimeter in thickness, the clarain appears homogeneous and has less luster than in the case in which the microvitrain is fine banded, that is, in laminas averaging 0.5–2 millimeters in thickness. Furthermore, the tenacity of the microbanded variety is greater than that of the finely banded variety. In lower-rank coals, such as subbituminous and bituminous high volatile *C*, the thicker microvitrain lenses show a tendency to slack after removal from the mine. Likewise, in clarains in which the microvitrain lenses reach a maximum thickness, the friability of the clarain is increased. Hence the common type of striped clarain is a coal which may show properties similar to the variety of cannel whose groundmass consists entirely of translucent attritus, or it may assume more the physical properties of vitrain.

All cannels are not composed of translucent attritus and minor amounts of microvitrain, for in some micrinite may be recognized. The opaque material occurs as thin shreds scattered throughout the translucent material, which is preponderant. Micrinite associated with cannels may be present in increasing proportion and may become the dominant constituent. Such coals are more closely allied to durain than to cannel; and Hickling[25] has demonstrated that all gradations exist between coals which are clearly cannels predominantly rich in translucent residuum and durain in which no translucent residuum is present.

Megascopic recognition of coals which belong to the cannel-durain series is not difficult in mature coals because of their characteristically dull luster, lack of banding, and conchoidal fracture. Nevertheless, the identification of the position of the coal in this series is uncertain on the basis of megascopic examination. When examined

[25] "The Properties of Coals as Determined by Their Mode of Origin," *Colliery Guard.*, Vol. CXLIV (1932), pp. 401–4.

microscopically, the amount of micrinite present demonstrates whether the coal is more closely allied to cannel or to durain.

One more type of composite coal is associated with the cannel-durain series. Such coal known as "semisplint" is characterized not only by the presence of micrinite and translucent attritus or collinite but by the presence of microvitrain. Semisplint is a composite coal whose characteristics indicate that it is more closely allied to splint coal and to durain than to cannel or the striped variety of clarain. The microscopic structure is definitely banded, owing to the presence of thin, rather smooth, bands of microvitrain. Generally semisplint consists of more or less equal amounts of microvitrain and micrinite, but certain varieties occur which contain collinite in proportions which cannot be considered minor. Coal of this type is very clearly a variety of clarain, whereas other semisplints containing only minor amounts of collinite are more properly varieties of durain. Semisplint is a tough coal which breaks into rudely shaped blocks and hence is commonly known as "block coal." The low friability of semisplint appears to be a function of the amount of micrinite present, since the friability increases as the micrinite decreases. Likewise, as the percentage of microvitrain and translucent attritus is increased, the properties of semisplint disappear, and the common type of striped clarain is developed.

CONCLUSIONS

The interrelationship of primary coals considered above demonstrates that no sharp boundary exists between banded and nonbanded varieties and that all are part of the same series of composite coals. Within any specific rank a coal's appearance is controlled by the primary coals which are present, each of which changes its properties with progressive metamorphism. Such behavior results in physical and chemical differences between composite coals, as the rank increases. Thus the coal investigator is faced with difficulties in properly classifying and describing the composite and primary coal types which constitute a coal stratum. Such descriptions are becoming increasingly necessary as supplements to chemical analyses in determining the proper utilization and preparation of the com-

posite coal. Little attempt has been made, however, to provide such description, and consequently no agreement exists concerning the procedure to employ.[26] There is need, therefore, of a uniform system of coal description by which the character of the composite coal may be known qualitatively and quantitatively.

In the foregoing paragraphs the reader's attention has been directed to the proposition that all coals appear to be composites of the primary coal types—vitrain, fusain, durain, and clarain-cannel. Hence, it should be proper to describe a composite coal in terms of these constituents. Such a procedure permits a statement concerning the percentage composition of the primary coals in a specific thickness of coal and a description of the appearance of the vitrain and clarain. The latter is particularly necessary not only because clarain and vitrain are the dominant constituents of all coals, but also because of the sensitivity to rank change in the case of vitrain and the great variation which may exist in the case of clarain. A statement concerning the average, maximum, and minimum thicknesses and distribution of the vitrain bands exclusive of the microvitrain conveys much information to the reader concerning the coal's appearance, friability, and utilization. Similarly, if the thickness and separation of the microvitrain bands and the ratio between durain and clarain-cannel are reported, a satisfactory description of clarain is given. Supplementary to descriptions of the primary coal types, use may be made of such terms as "cannel," "splint," "semi-splint," or "block" coals, which are at present in common usage to designate coals possessing certain characteristic properties. Such terms are extremely useful in describing certain coal types, but their present loose usage should be abandoned, and they should be redefined as coals whose percentage composition of the primary types lies within certain arbitrary, but carefully selected, limits. Other terms representing different coal types should be introduced to designate coals possessing specific characteristics, much as in the manner

[26] The United States Bureau of Mines has employed a graphic method of coal description in some of their publications. See R. Thiessen and G. C. Sprunk, "Microscopic and Petrographic Studies of Certain American Coals," *U.S. Bur. Mines, Tech. Paper 564* (1935), p. 36.

of a classification of igneous rocks. It will be possible, then, to employ such statements as "splint," "bituminous high-volatile B" (durain 70 per cent, vitrain 0 per cent, fusain 10 per cent, clarain-cannel 20 per cent; microvitrain 5 per cent of clarain, and in bands 0.5 mm. thick, spaced at intervals of 20 mm.) to describe a particular type of coal. Furthermore, a distinct comparison may be drawn with another portion of the same bed, which might also be a splint of bituminous high-volatile B rank but have a different percentage composition of primary coals. Until some similar system, which is at least partly quantitative in nature, is proposed and adopted, coal description and classification can make little progress.